20/04/06
TD-06-016

Spike studies using Superconduting strands

Test results of a 1 mm Modified Jelly Roll with a low copper residual resistivity ratio

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This note summarizes the test results of voltage spike studies using a 1 mm MJR strand with a low copper Residual Resistivity Ratio. During the test voltage spikes were recorded while the magnetic field or the current was ramped up until the strand had quenched.

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1) INTRODUCTION

The main goal of the strand tests was to try to identify the origin (strand or cable) of voltage spikes and to collect further information about thermo-magnetic instabilities. In order to achieve this goal the Voltage Spike Detection System (VSDS) [1] was used in parallel to the critical current (I_c) measurement system of the Short Sample Test Facility (SSTF) [2]. Description of the test set-up including the details of the ***1a*** sample used in these tests can be found in TD-05-029 [3].

For most of the test the ***1a*** sample which is a 1 mm MJR strand was wound onto a Titanium alloy barrel except for the copper Residual Resistivity Ratio (RRR) measurement. For the RRR measurement a G-10 barrel was used to avoid current sharing between the barrel and the strand itself [4]. The RRR was very low, around 7.

The test has been subdivided into three parts:

1) Critical current measurement using the V-I technique (ramping the strand current at fixed external magnetic field and temperature).
2) V-H measurements (ramping the background magnetic field at fixed transport current and temperature).
3) V-I measurements at low fields where the quench current (I_q) is lower than I_c.

During the whole experiment the Voltage Spike Detection system was activated in order to collect as much voltage spike data as possible.

2) CRITICAL CURRENT MEASUREMENTS

Strand samples have been characterized by measuring the V-I curve and determining the critical current (I_c) value by observing the reversible transition between the superconducting and normal states. This measurement starts at high field values (15 T) and it is repeated at lower and lower field values down to a minimum field at which the reversible transition to the normal state is observed.

In fig. 2.1.1 the reversible transition of the strand at 15 T is shown: increasing the current above I_c, 326 A, the superconductor gradually becomes more and more resistive. The criteria to determine the critical current and its error are described in TD-04-055 [5]. In order to save time, during the V-I measurements, we generally use two different current ramp rates: a fast ramp rate initially and a slower one in the last part of the ramp. I_c measurements are summarized in Tab. 1. The columns contain: the identification symbol of the experiment; the ramp number; the current value (V-H measurement) or the current interval with the ramp rate used prior to quenching the sample (V-I measurement); the magnetic field value (V-I measurement) or the magnetic field interval (V-H measurement); the current ramp rate (last part of the ramp); the magnetic field ramp rate; the quench current; the quench magnetic field; the number of spikes collected before the quench; if the quench data was saved by the VSDS; the quench location; if the quench was triggered by a voltage spikes; comments.

Tab.1 Critical current measurements

ID	Ramp #	I	B	dI/dt	dB/dt	Iq	Bq	# of Spikes	Quench Data	Quench Location	Quench Trigger	Comment
		A	T	A/sec	T/min	A	T					
■ ○	1	**0**	**0→ 12**	0	1	_	_	8	_			spike below 5T
▼R	2	**150→ 365**	**15**	1	0	365	15	3	N/A	_	_	0→ 150A 5A/sec
▼R	3	**400→ 462**	**14**	1	0	462	14	0	yes	splice2	_	0→ 400A 5A/sec
▼R	4	**500→ 576**	**13**	1	0	576	13	0	yes	splice2	_	0→ 500A 5A/sec
▼R	5	**600→ 708**	**12**	1	0	708	12	0	yes	splice2	_	0→ 600A 5A/sec
▼R	6	**750→ 858**	**11**	1	0	858	11	0	yes	splice2	_	0→ 750A 5A/sec
▼R	7	**700→ 850**	**11**	1	0	850	11	0	yes	splice2	_	0→ 700A 5A/sec
▼M	8	**850→ 1000**	**10**	1	0	1000	10	0	yes	splice2	_	0→ 850A 5A/sec
▼M	9	**950→ 1173**	**9**	1	0	1173	9	0	yes	splice2	_	0→ 950A 5A/sec
▼	10	**950→ 1173**	**9**	1	0	1173	9	1	yes	splice2	_	0→ 950A 5A/sec; spike @ ≈1100A
□ ○	11	**0**	**9→ 0**	0	1	_	_	8	_	_	_	

■ ○ ➔ Ramping up the field with no transport current
□ ○ ➔ Ramping down the field with no transport current
▼R ➔ V-I measurement; reversible transition of the superconductor was observed
▼M ➔ V-I measurement; premature quench; sample was magnetized
▼ ➔ V-I measurement; premature quench; sample was demagnetized by a previous quench
S ➔ Service magnetic field ramp in order to change the field for the next measurement
■ ➔ V-H measurement with transport current in the sample, ramping up the field
□ ➔ V-H measurement with transport current in the sample, ramping down the field

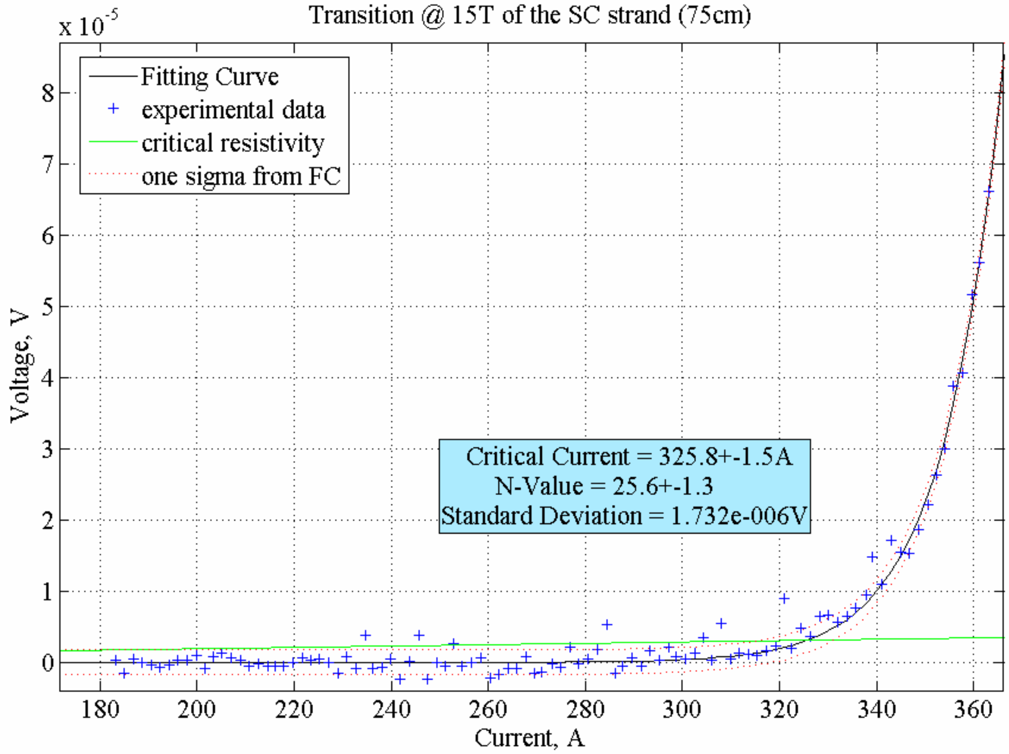

Fig.2.1.1 Superconductor transition at 15T, slow DAQ data

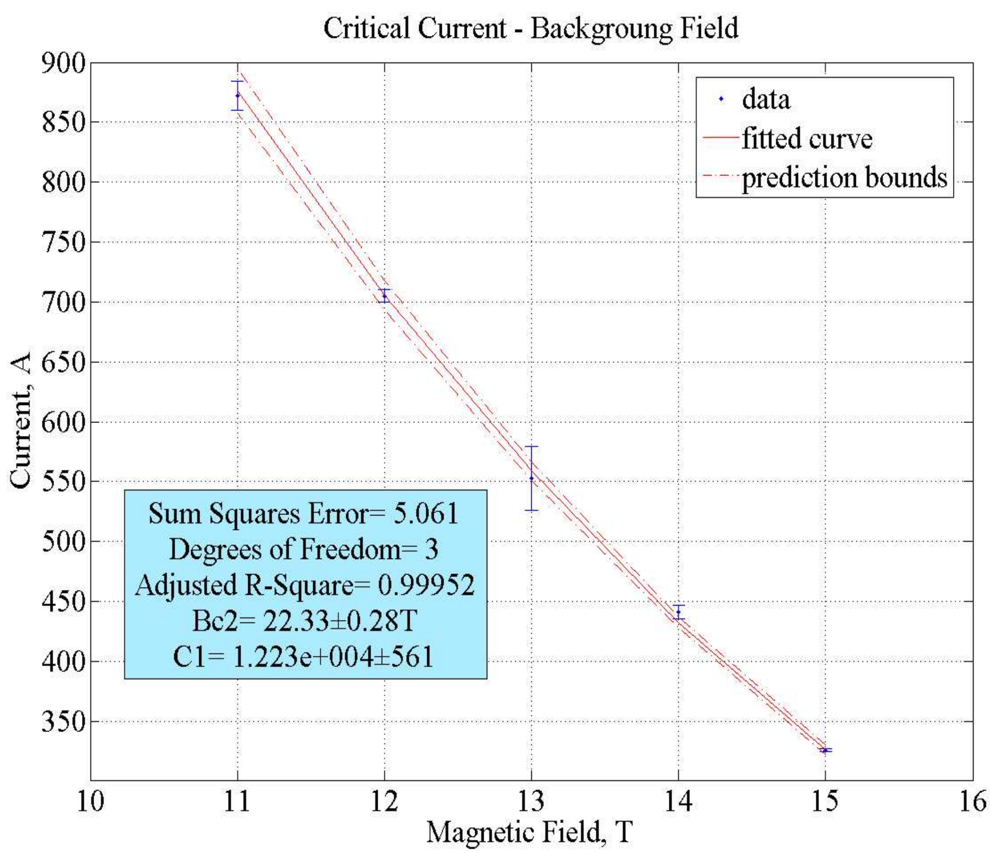

Fig. 2.1.2 Critical current measurement results

In fig. 2.1.2 I_c measurements results are presented. The diamond symbols with error bars represent the data. The read line corresponds to the parameterization of the I_c obtained from the fit [4]. The errors of the measurements and the prediction bound of the fitting have been calculated with a confidence level of 95%. Below 11T the critical current could not be measured since the sample quenched before reversible transition could have been observed. This field value is consistent with other tests of 1 mm MJR strands performed at the SSTF. Result of the fit is excellent: χ square (indicated as R-Square in the plot) is very close to one. In order to obtain such a good fit self field effects had to be included [4].

3) V-H measurements

In this test the magnetic field has been swept up or down in the low field region (between 0 and 4T). At the beginning of the test the current value was sufficiently high to guarantee to quench the strand. The experiment is then repeated at lower and lower current values until the minimum quench current (I_{qm}) between 0 and 4 T was observed. The I_{qm} was determined with an accuracy of 50A.

In order to eliminate the magnetization pre-history, before performing the V-H measurement, the current is increased until the sample quenched.

This kind of test is very interesting because the strand gets more unstable with respect to the V-I measurement (the quench current in this case can be more than twice smaller). This is probably due to the fast release of the magnetization energy stored in the strand filament ('flux jump'). While the current is ramped up with a fixed magnetic field the filaments have much less magnetization. Actually if we ramp the current starting with a sample completely not magnetized, the filaments stay practically not magnetized for the entire "ramp to quench" process. This kind of flux jump has been observed many times during magnetization measurement at low fields. In fig. 3.1.1 a typical magnetization measurement is shown for a 1mm MJR strand. Tab. 2 summarizes the results of the V-H experiments including some experimental details.

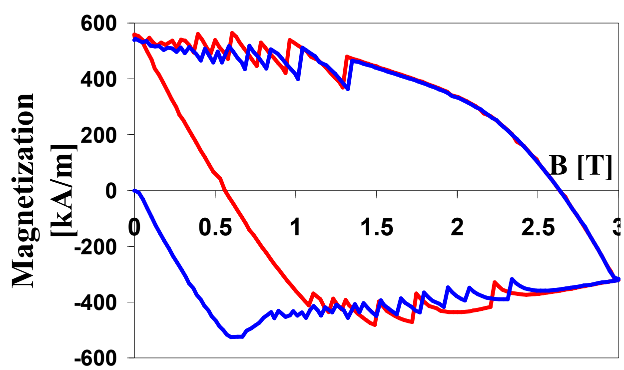

Fig. 3.1.1 Magnetization measurement on a 1mm MJR

4) V-I measurements at low fields

These types of measurements have started with 0T magnetic field then the field value was increased in steps of 1T up to 8 T.

Tab. 3 summarizes the results of the V-I experiments including some experimental details; the different symbols have the same meaning as it was described in the previous paragraph.

Tab. 2 Quench current measurement sweeping the magnetic field

ID	Ramp #	I	B	dI/dt	dB/dt	Iq	Bq	# of Spikes	Quench Data	Quench Location	Quench Trigger	Comment
		A	T	A/sec	T/min	A	T					
▼M	12	**0→802**	**0**	N/A	0	_	_	9	_	_	_	ramp I, steps 20A
▼	13	**0→1405**	**0**	20	0	1405	0	1	yes	coil1	spike	
■	14	**1100**	**0→0.46**	0	1	1100	0.46	6	yes	coil1	spike	collected other spikes after quench
S	15	**0**	**0.98→0**	0	1	_	_	1	_	_	_	
▼M	16	**0→980**	**0**	20	0	980	0	11	yes	coil1	spike	1° Spike Fake; spike ≈ magnets
▼	17	**850→1000**	**0**	≈2	0	_	_	2	_	_	_	0→850A 10A/sec
■	18	**1000**	**0→0.63**	0		1000	0.63	7	yes	coil1	spike	collected other spikes after quench
S	19	**0**	**0.81→0**	_	1	_	_	3	_	_	_	
▼M	20	**0→855**	**0**	20	0	855	0	7	yes	coil1	spike	1° Spike Fake
▼	21	**850→900**	**0**	≈2	0	_	_	2+1	_	_	_	0→850A 10A/sec; 1spike 840A
■	22	**900**	**0→0.69**	0	1	900	0.69	5	yes	coil1	spike	1° 0.55T; collected other spikes after quench
S	23	**0**	**0.81→0**	_	1	_	_	4	_	_	_	
▼M	24	**0→1000**	**0**	20	0	1000	0	15	yes	coil2	_	1° Spike Fake
■	25	**800**	**0→0.61**	0	1	800	0.61	7	yes	coil2	spike	collected other spikes after quench
S	26	**0**	**0.75→0**	_	1	_	_	4	_	_	_	
▼M	27	**0→950**	**0**	20	0	950	0	10	yes	coil1	spike	1° Spike Fake
■	28	**700**	**0→0.92**	0	1	_	_	11	_	_	_	1° 0.5T; stopped
■	29	**700**	**0.92→12**	0	1	_	_	19	yes	splice2	_	last 4.3T;
□	30	**650**	**12→1.36**	0	1	650	1.36	4	yes	coil2	spike	1° Spike Fake;
S	31	**0**	**1.36→0**	_	1	_	_	6	_	_	_	
▼M	32	**500→1090**	**0**	20	0	1090	0	6	yes	coil2	spike	1° 600A; 0→500A steps 15A,
■	33	**700**	**0→1.57**	0	0.2	700	1.57	14	yes	coil1	spike	
S	34	**0**	**1.7→0**	_	1	_	_	7	_	_	_	
▼M	35	**0→880**	**0**	20	0	880	0	6	yes	coil2	spike	1° Spike Fake
■	36	**600**	**0→4**	0	0.2	_	_	16	_	_	_	11 spikes 0.44-1.6T; 5 spikes 2.7-3.78T;
	37											Current Problems
□	38	**600**	**4→0**	0	1	_	_	24	_	_	_	2° 25mv probably at 1.2T; magnet shape

Tab.3 Quench current measurement ramping the current

ID	Ramp #	I	B	dI/dt	dB/dt	Iq	Bq	# of Spikes	Quench Data	Quench Location	Quench Trigger	Comment
		A	T	A/sec	T/min	A	T					
▼M	39	**0→940**	**0**	20	0	940	0	4	yes	coil2	_	
▼	40	**800→1035**	**0**	1	0	1035	0	1	yes	coil1	spike	0⟶800A 20A/sec
▼M	41	**0→1560**	**1**	20	0	1560	1	0	yes	coil2	_	fast quench; no data recorded 0-1T
▼	42	**1200→1282**	**1**	1	0	1282	1	0	yes	coil2	_	0⟶1200A 20A/sec
▼	43	**1200→1317**	**1**	1	0	1317	1	0+1	yes	coil2	_	0⟶1200A 20A/sec
▼	44	**0→1260**	**1**	20	0	1260	1	0	yes	coil2	spike	
▼M	45	**0→1095**	**2**	20	0	1095	2	1	yes	coil1	spike	1° Spike Fake; no data recorded 1-2T
▼	46	**1000→1180**	**2**	1	0	1172	2	1	yes	coil2	spike	0⟶1000A 20A/sec
▼M	47	**0→1060**	**3**	20	0	1060	3	1	yes	coil2	spike	no data recorded 2-3T
▼	48	**950→1132**	**3**	1	0	1132	3	0+2	yes	coil2	spike	0⟶950A 20A/sec
▼M	49	**0→1090**	**4**	20	0	1090	4	1	yes	coil2	_	no data recorded 3-4T
▼	50	**950→1069**	**4**	1	0	1069	4	1+2	yes	coil1	_	0⟶950A 20A/sec; 1 spike after quench
▼M	51	**0→945**	**5**	20	0	945	5	0	yes	coil1	spike	no data recorded 4-5T
▼	52	**800→1065**	**5**	1	0	1065	5	1	yes	coil2	spike	0⟶800A 20A/sec
▼M	53	**0→1020**	**6**	20	0	1020	6	0	yes	coil1	_	no data recorded 5-6T
▼	54	**900→991**	**6**	1	0	991	6	0	yes	coil2	_	0⟶900A 20A/sec
▼M	55	**0→905**	**7**	20	0	905	7	0	yes	coil2	_	no data recorded 6-7T
▼	56	**750→1037**	**7**	1	0	1037	7	0	yes	coil2	_	0⟶750A 20A/sec
▼M	57	**0→1280**	**8**	20	0	1280	8	1	yes	coil1	_	no data recorded 7-8T
▼	58	**0→1240**	**8**	20	0	1240	8	0	yes	coil1	_	
▼	59	**1100→1207**	**8**	1	0	1207	8	0	yes	coil1	_	0⟶1100A 20A/sec
□	60	**600**	**8→0**	0	1	_	_	30	_	_	_	1° 10mv 1.6T; magnet shape

5) Quench Current

In fig 5.1.1 the I_q is plotted as a function of the background magnetic field. The triangles represent the V-I measurements while the asterisks the V-H measurements.

During V-I measurement we observed reversible transition down to 11 T. Further decreasing the field from 10 to 8 T the I_q was less than the I_c but it was still increasing; repeating the measurement starting with the sample demagnetized, the I_q did not change significantly. Decreasing the field further to 7 T the I_q had a big drop. This drop of the I_q is more noticeable by plotting the ratio of I_q and I_c: at 8 T the current ratio was ~0.8 while at 7 T it was only ~0.5. In fig. 5.1.2 the normalized current ratio is shown as a function of the peak field the sample was exposed to. The importance of using the peak field in the calculation of the I_c at low background fields was described in [6]. Below 7 T further decreasing the magnetic field the current ratio decreases almost linearly. These measurements at low field were repeated starting with non-magnetized sample as well. Even if the magnetization current plays probably a significant role in the I_q values at very low field region (0-2 T), this is not so significant for the current ratio. It is also important to notice that prior to these measurements (between 0 and 7 T) the strand was exposed to higher Lorentz forces during I_c measurements. This means that mechanical instability can not be the reason for premature quenches. From these results we can conclude that the 1 mm MJR with a low RRR is strongly self-field unstable [7].

During the V-H measurements the minimum quench current, I_{qm}, further decreased. Sweeping up the magnetic field the I_{qm} was 700 A @ 1.57 T while sweeping down it was 650A @ 1.36 T. Comparing the results with magnetization measurements (fig. 3.1.1) it is interesting to notice that the minimum quench current field region correspond to the biggest filament flux jump region of the magnetization measurements.

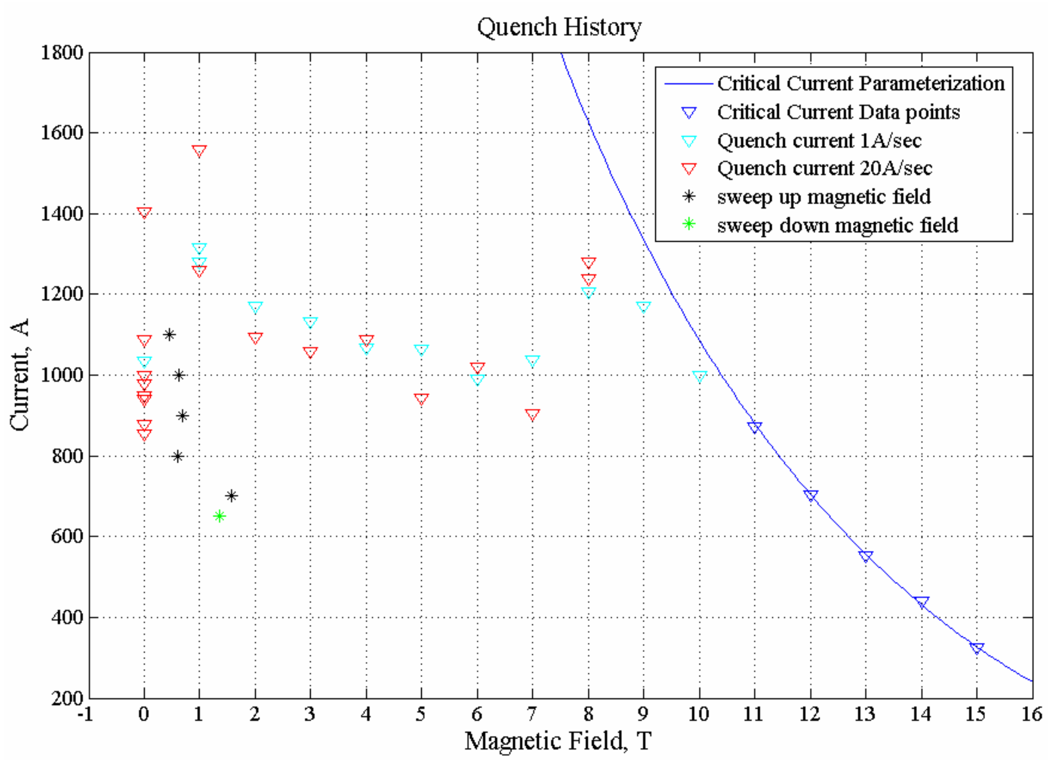

Fig.5.1.1 Quench current as a function of the background magnetic field

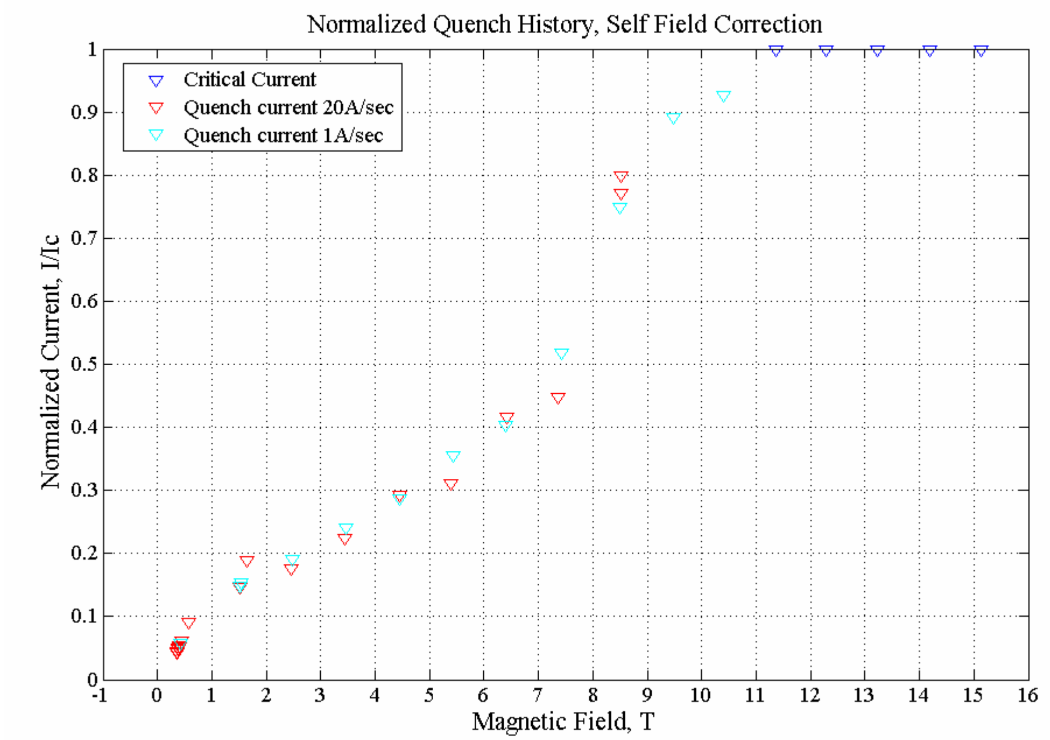

Fig. 5.1.2 Normalized quench current as a function of the magnetic field peak

6) Number of spikes detected

Analyzing the tables 1, 2, 3 it can be concluded that during:

1) V-I measurements at fields >= 1 T there were only few spikes, 1 +-1;
2) V-I measurements at 0 T with the sample magnetized there were about 9+-5 spikes;
3) V-I measurements at 0 T with the sample partially demagnetized by a previous quench there were about 1+-1 spikes;
4) V-H measurements with no transport current ramping up the magnetic field starting with the sample demagnetized, 8 spikes between 0.5 and 5 T were collected;
5) V-H measurements with no transport current ramping down the magnetic field starting from 9 T, 8 spikes were collected between 1.6 and 0 T;
6) V-H measurements with a transport current, the number of spikes increased sensibly (three four times) with respect to 4 and 5 but the field range where they happened was the same.

From these results with the magnetization measurement results suggests that most of the spikes are consequences of filament flux jumps.

7) Spike characterization

The signal shape exhibited strong correlation with physical conditions of the sample: presence of filament magnetization and/or transport current. We were able to distinguish four different type of spikes based on the physical condition of the sample.
A general characteristic feature of the signals was that a fast spike in one half of the sample induced an opposite smaller signal in the other half of the sample even if the transport current was zero.

Since the polarity of the voltage signals depends on the direction of the external magnetic field and the direction of the applied transport current it is important to show how the setup was made. Fig 7.0.1 shows the schematic of the coil sample, the direction of the external magnetic field, the direction of the transport current, and the location of the voltage taps. Voltage taps were connected to the DVM such away to obtain positive voltage signals if the sample is resistive and transport current is present. From fig. 7.0.1 we can also conclude that sudden flux increase will generate negative voltage signals.

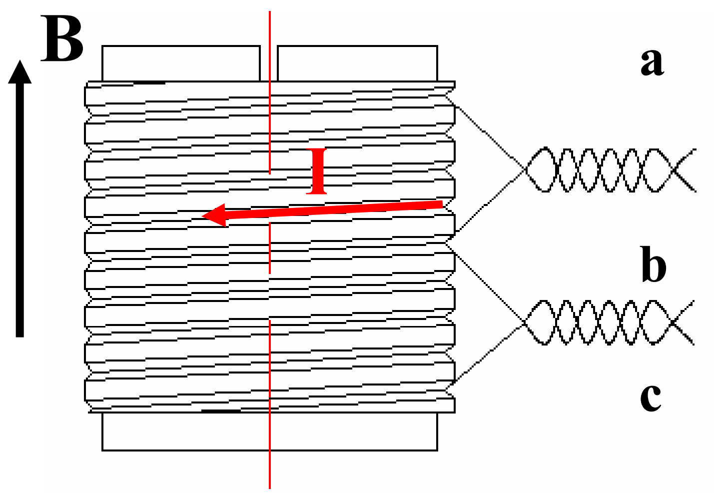

Fig. 7.0.1 Magnetic field and current direction in SSTD set up

7.1) 'Magnetization' spikes

This type of spikes has been observed clearly during V-H measurements with no transport current in the strand. They have been named 'magnetization' spikes because they are due to the demagnetization process of the strand filaments ('flux jumps').

Increasing the magnetic field, starting with a non-magnetized sample the filaments get negatively magnetized, however ramping down the magnetic field the filaments get positively magnetized.

In our test configuration the 'magnetization' spikes polarity was the same as the magnetization polarity.

Within this magnetization spike category we found two subcategories: in one case the spike propagates from one half of the coil to the other half, in the other case it stays within one half of the coil. For this reason they were named 'propagating' and 'not propagating' magnetization spikes.

The ‘propagating magnetization’ spikes have been observed during up or down ramp of the magnetic field at zero transport current. In this case the magnetization was almost uniform in the entire sample (last 6 spikes of ramp 1, all 8 spikes of ramp 11). Fig. 7.1.1 shows one of these spikes; to be able to compare the two signals easily, the second signal has been offset. These spikes have similar signal shape in both halves. Removing the high frequencies oscillations (above 1 kHz) by applying a moving average over 100 data points (1ms), fig. 7.1.2, it was found that the signal of each half coils can be divided into two parts: in the first part, lasting 4-8 ms, the average of the two half coil signals are different from each other and they exhibit fast voltage variation; in the second part there is a ‘smooth oscillating tail’ where the two half coil signals are equal and they follow a dumped slow sinusoidal shape ($f(t)=a\cdot\sin(\omega\cdot(t-t_0))\cdot e^{[-b\cdot(t-t_0)]}$) oscillation. The period T_{Ave} ($2\pi/\omega$) is of the order of 10 ms and the time constant of the exponential τ_{Ave} ($1/b$) is about 3 times smaller ~3ms. The analysis of the moving average signals shows that flux jumps propagate longitudinally, fig.7.1.3 & 7.1.4. Assuming that the spike propagates through the entire strand the spread in time of the first part of the signal (4-8ms) might be explained by the location of the spike origin. For example if the time of the first part of the signal is 4 ms the flux jump should have started in the middle of the coil. If 8 ms time was observed the flux jump should have started in the end of the coil. Comparing a Fast Fourier Transform (FFT) of the noise (200ms window before the spike) with a FFT of the spike (25 ms window containing the spike) we found that generally the fast oscillations have a frequency between ~2 and ~15 kHz, fig. 7.1.5, 7.1.6. In appendix A there are the plots of all the ‘propagating magnetization’ spikes collected during V-H measurements with no transport current in the strand. For each event there are three plots showing:1) the signals of the two half coils; 2) the sum and difference of the two half coils signals; 3) the two half coils signals moving average.

During a V-H measurement with sufficiently high transport current, at certain field value, the sample quenches. If after the quench the magnetic field ramp was not stopped (the transport current at this point was zero), we were able to observe ‘no propagating magnetization’ spikes (lot of examples can be found in appendix B for ramps 14, 18, 22, 25 where spikes occurred after the sample has been quenched). In this case the spike does not propagate from one half to the other, fig. 7.1.7, 7.1.8. The lack of complete longitudinal propagation of the flux jump is probably due to the non uniformity of the magnetization caused by the quench. For these types of spikes the signal is negative which is in a good agreement with expectations since the sample was negatively magnetized. The shape of these signals can be divided also into two parts: the first part has a sharp peak much shorter in time (0.05-0.5 ms); the shape of the second part of the signal is similar to that of the propagating spikes (‘smooth oscillating tail’). In this case no high frequency oscillations have been observed.

It is important to notice that ‘propagating magnetization’ spikes we observed only if the entire sample was uniformly magnetized. If the magnetization was removed from a fraction of the sample by quenching the strand only ‘no propagating magnetization’ type spikes were observed. One can speculate that the ‘propagating magnetization’ spikes should be associated with global filament flux jumps, where by definition global filament flux jump involves vortex in motion in the entire volume of the filament (but not everywhere at the same time). The flux jump does not develop instantaneously in the longitudinal direction and above all, even if the sample is uniformly magnetized, the flux jump will not necessary propagate longitudinally for the whole sample.

In literature there is also another important definition regarding flux jumps: complete and partial flux jumps. The part of superconductor, which have had a flux jump, in case of complete flux jumps turns to normal state, while in the other the jump self-terminates when the temperature is still less than the critical temperature [8].

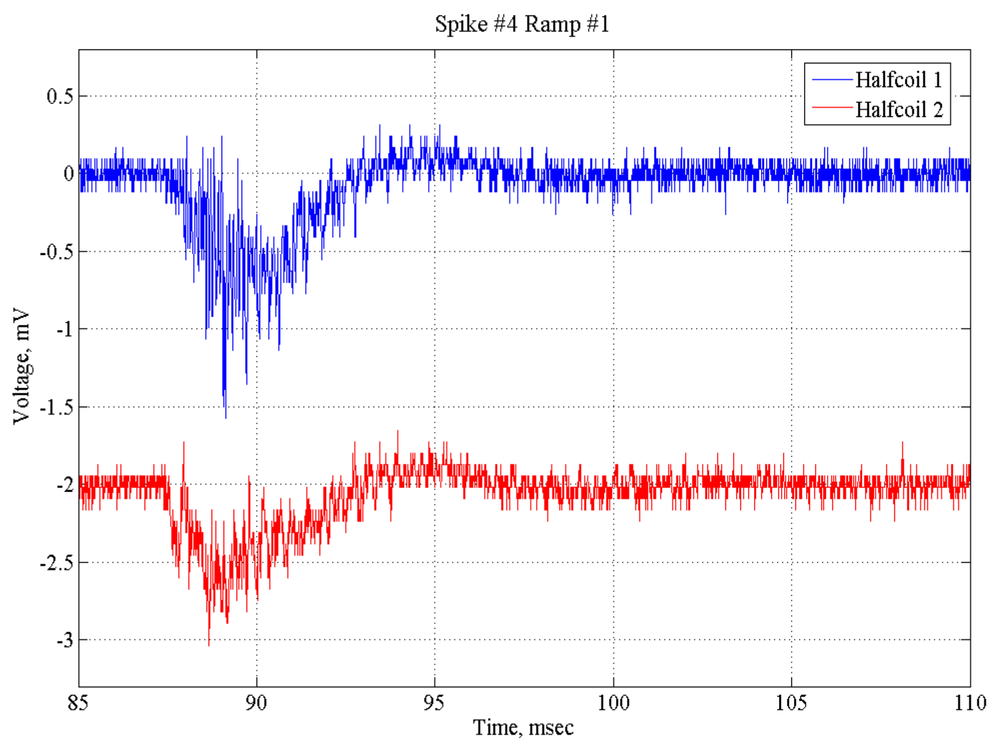

Fig. 7.1.1 Propagating magnetization spike; negative magnetization

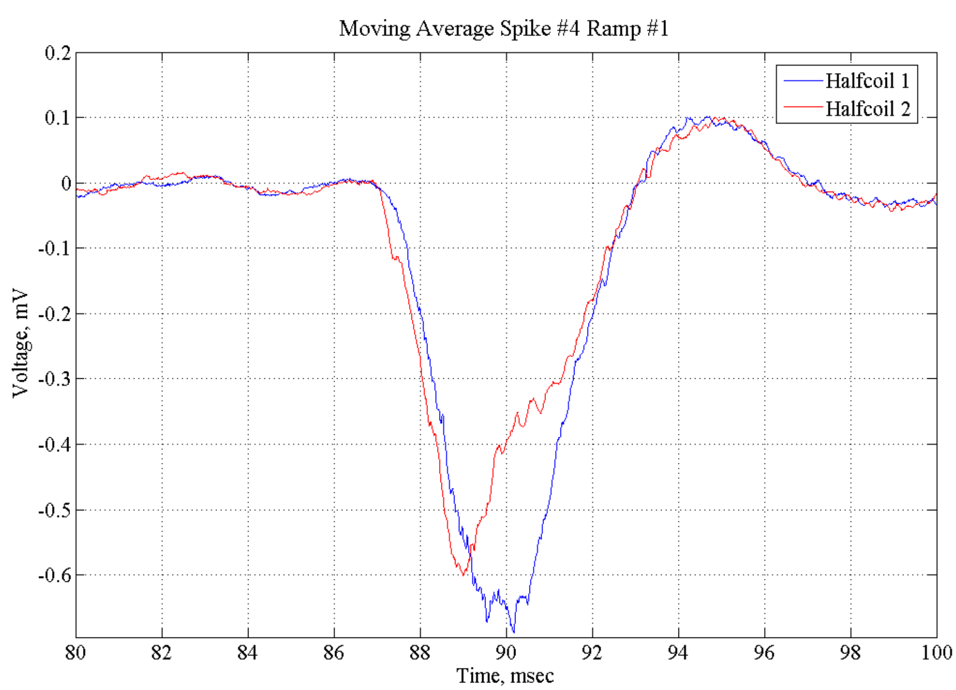

Fig. 7.1.2 Propagating magnetization spike; negative magnetization

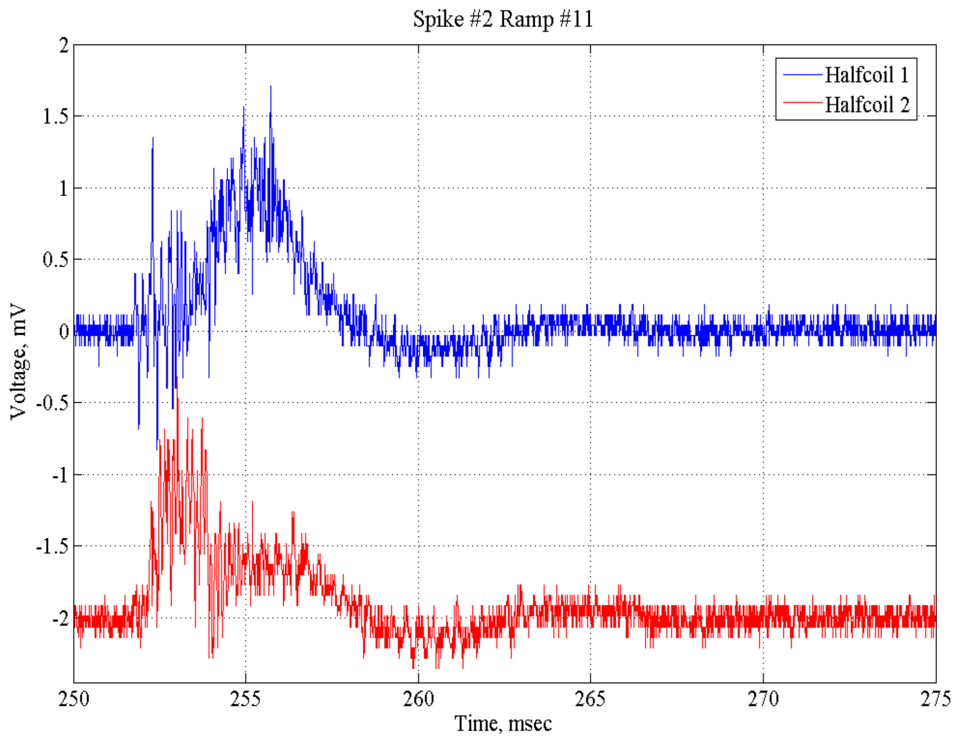

Fig. 7.1.3 Propagating magnetization spike; positive magnetization

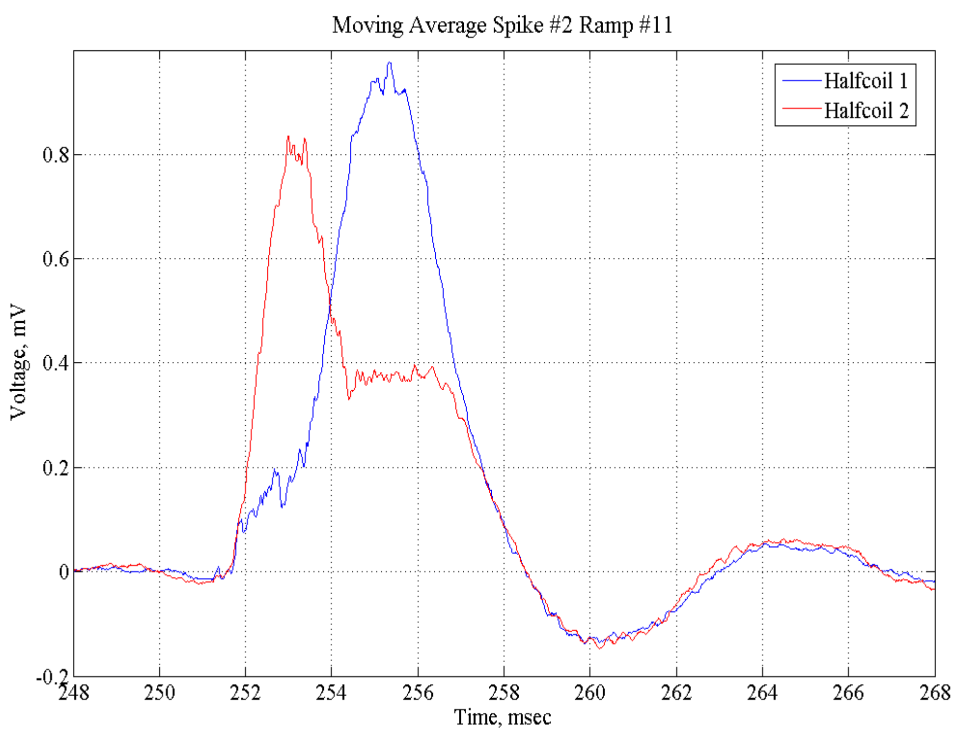

Fig. 7.1.4 Propagating magnetization spike; positive magnetization

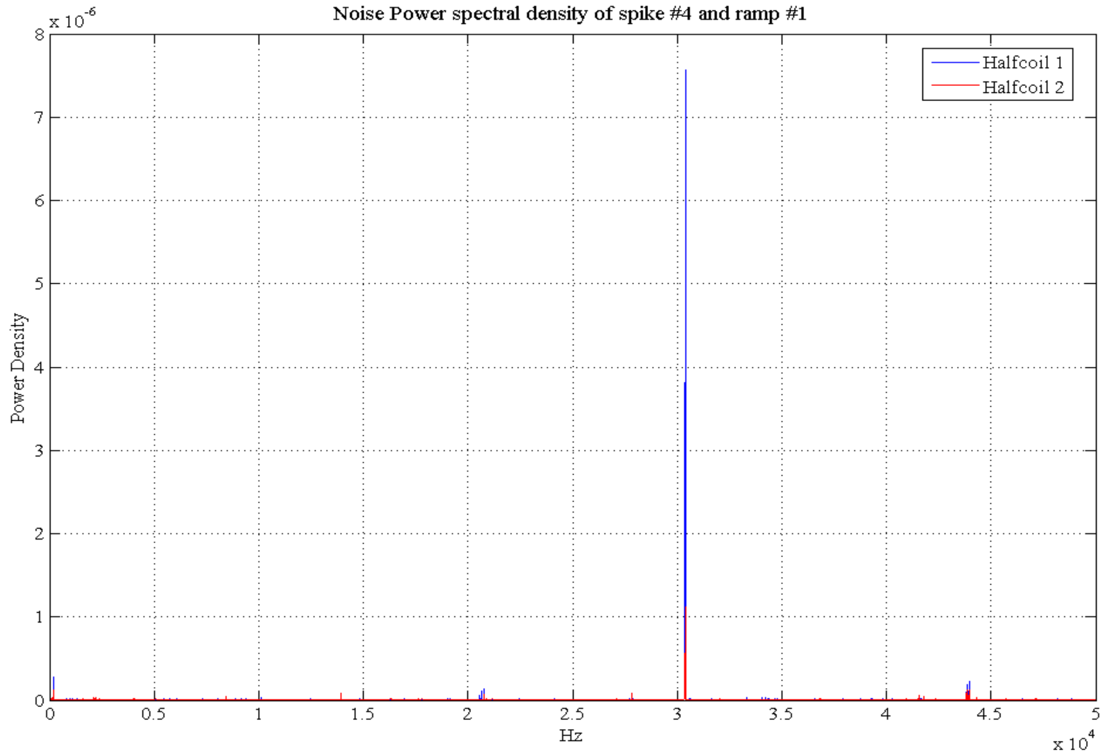

Fig. 7.1.5 FFT of the noise before the voltage spike showed in fig. 7.1.1

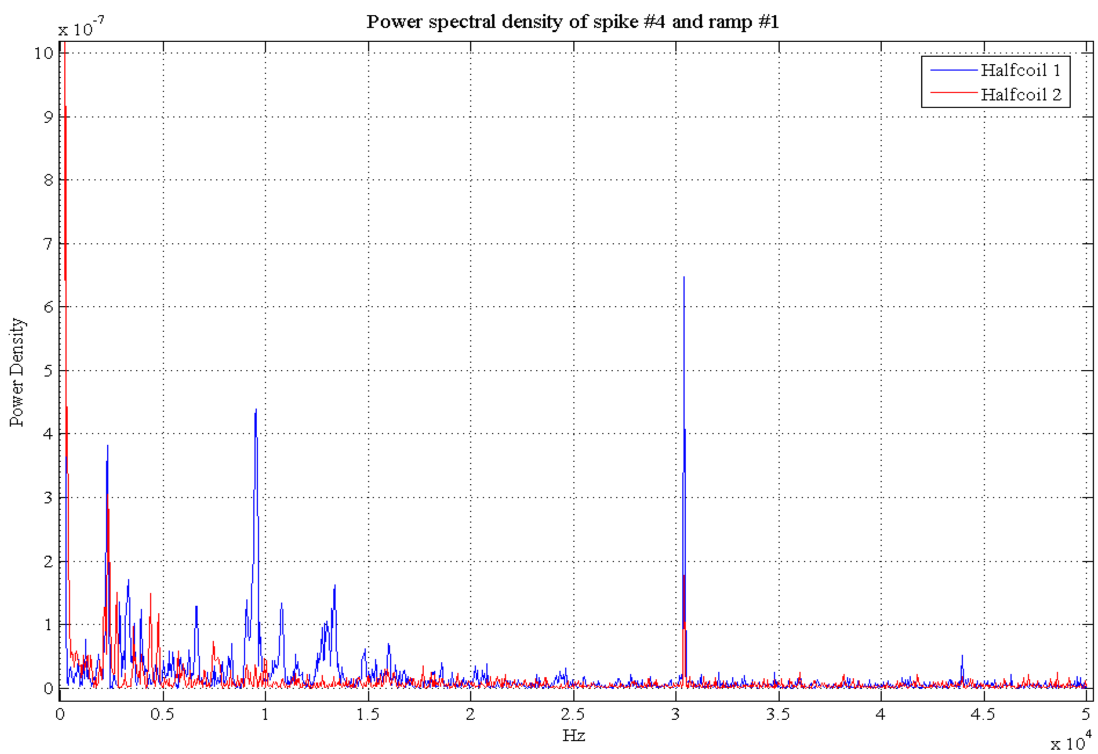

Fig. 7.1.6 FFT of the voltage spike signal showed in fig. 7.1.1

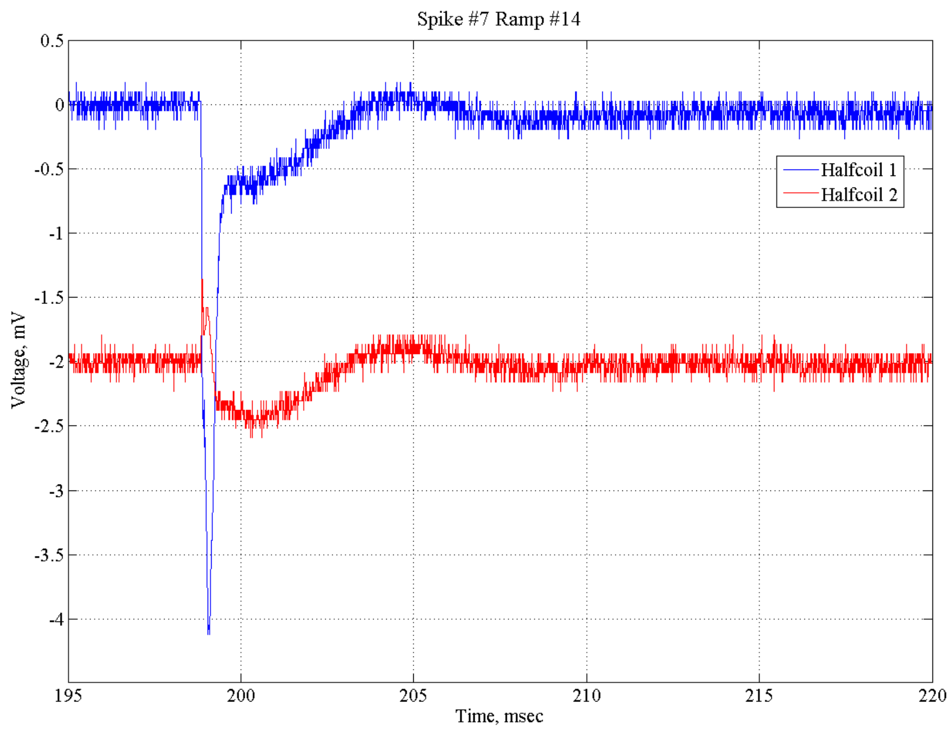

Fig. 7.1.7 No propagating magnetization spike; negative magnetization

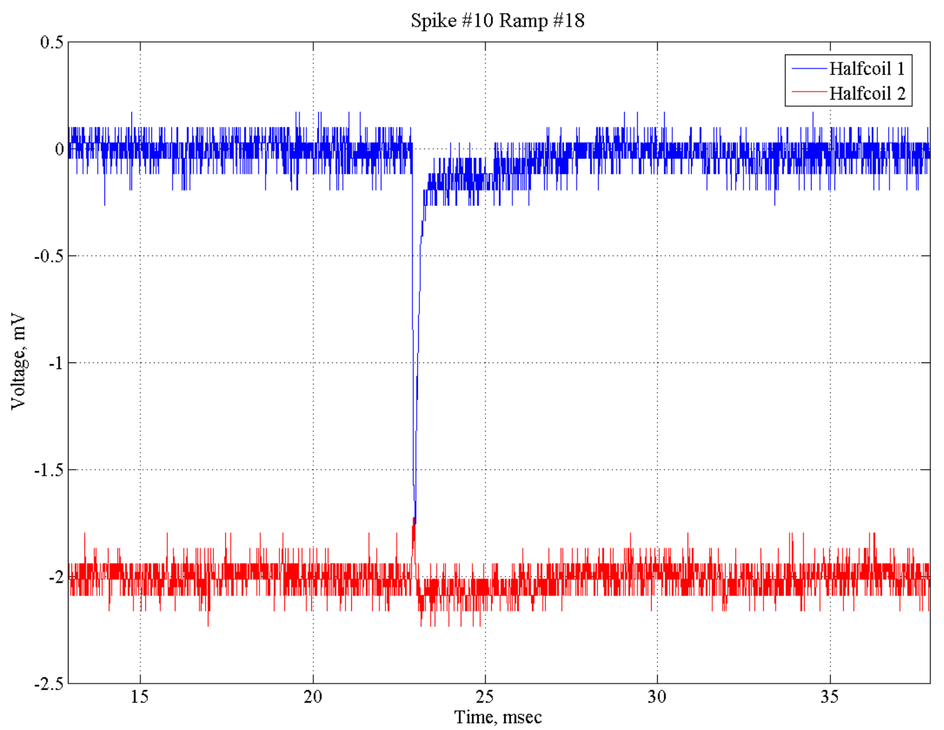

Fig. 7.1.8 No propagating magnetization spike; negative magnetization

7.2) 'Transport current' spikes

During V-H measurements when transport current was present and the magnetic field was ramped up the polarity of the observed voltage spikes was always positive regardless that the sample was negatively magnetized. The shape of these spikes was also different than that of the magnetization spikes. These types of spikes were named 'transport current' spikes, fig. 7.2.1. Due to the above fact it means that transport current spikes can not be associated with filament demagnetization; most likely these signals are related to self-field instability and in particular to the redistribution of the transport current within the strand. The signal is characterized by short rise and fall time (few tens of μs) without the 'smooth tail' that was observed in 'magnetization' spikes.
The spikes collected during ramps 28 and 33 happened above ~0.5T, this guarantee that the sample was not positively magnetized. In appendix C the plots of transport current spikes during these two ramps are shown.

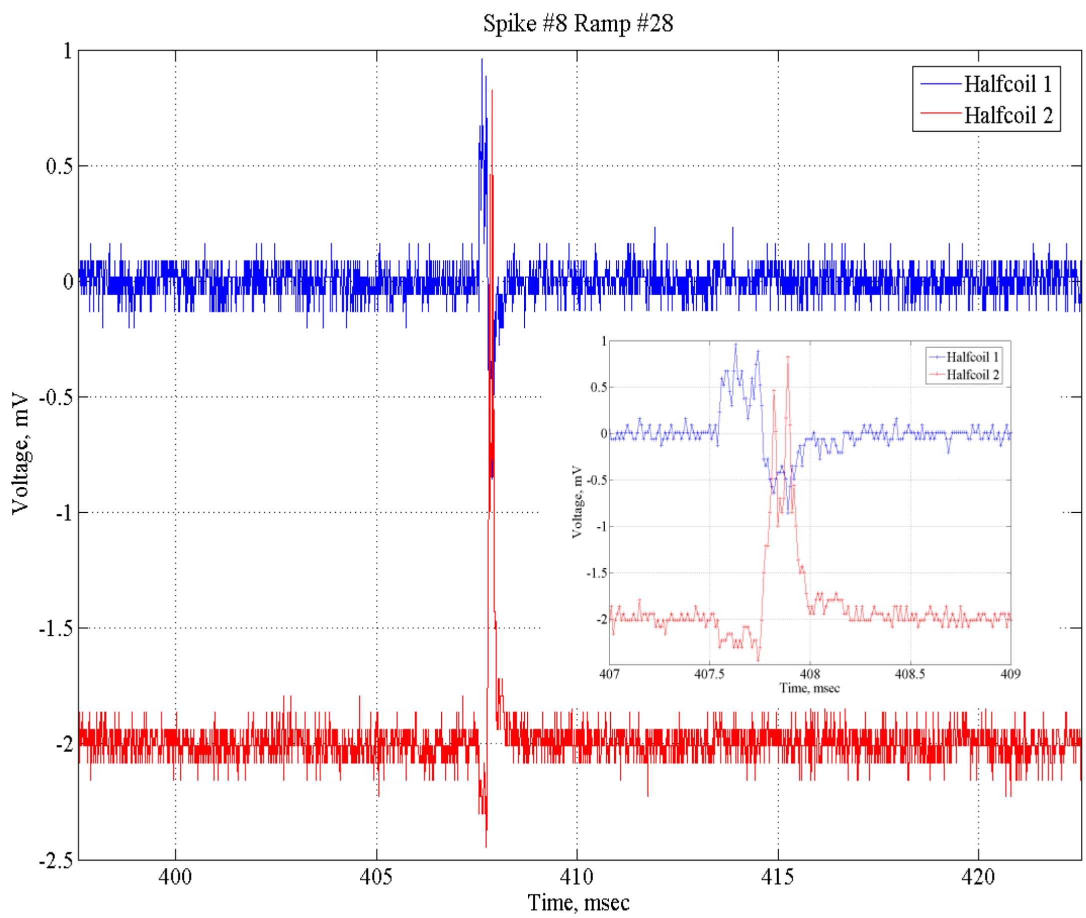

Fig. 7.2.1 Transport current spike

7.3) 'Mixed' spikes

Some of the spikes seem to be a superimposition of 'transport current' and 'magnetization' spikes so we named them mixed spikes. They have been observed while the magnetic field was swept with a fixed transport current in the sample. In fig. 7.3.1 it is shown how a mixed spike look like in the case the sample is negatively magnetized; there is a 'transport current' spike followed by a negative 'global magnetization' spike. It is interesting to notice that in this case the 'smooth tail' of the 'global magnetization' spike does not have a sinusoidal shape.

In appendix D the plots of the most clear 'Mixed' spike of ramps 29 and 36 are shown.

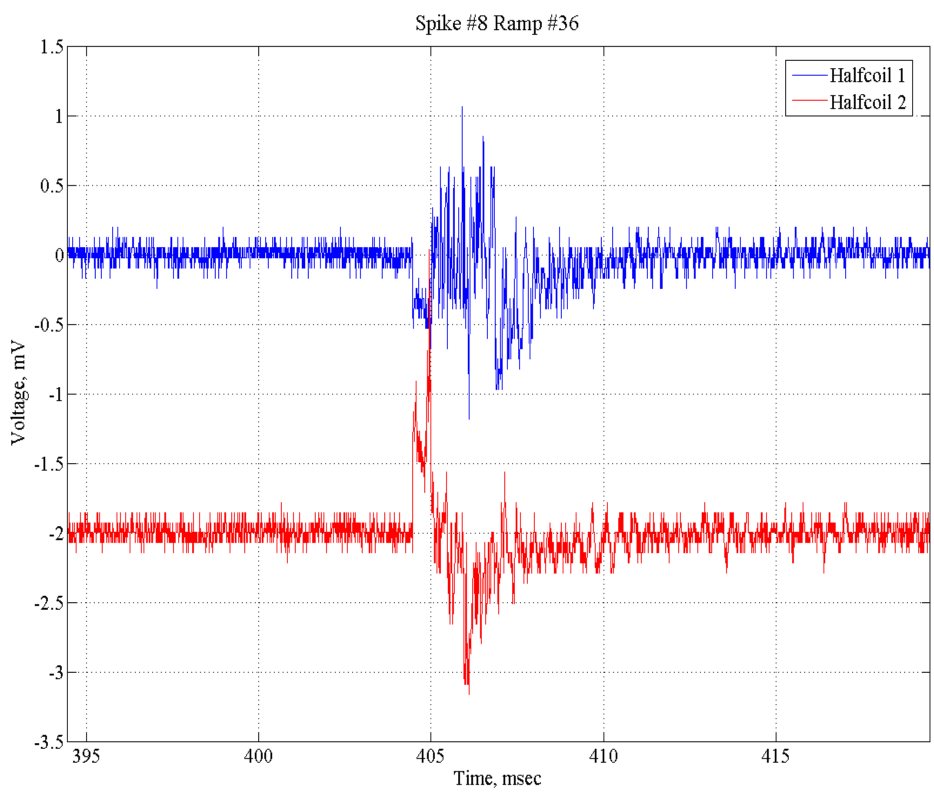

Fig. 7.3.1 Mixed spike

8) Spikes signal shape

In this paragraph the various spikes signal shapes, which occurred during the different experiments, have been summarized.

8.1) V-I measurements: 0 T and the sample was positively magnetized

In these measurements (ramps 12, 16, 20, 24, 27, 32, 35, 39) the signal is positive and it does not have oscillations. It is characterized by short rise and fall time (few tens of μs), fig. 8.1.1. The signal duration time was 0.2-3 ms and the maximum signal amplitude was about 10 mV, fig. 8.1.2. These voltage spikes can propagate from one half to the other as it is shown in fig. 8.1.3.

Based on the shape and polarity of these signals we can not exclude the possibility that these spikes are ‘magnetization’ spikes. On the other hand during V-I measurements at different magnetic field values when we were able to distinguish between magnetization and transport current spikes (by observing the expected polarity of the signals), ‘magnetization’ spikes have never been observed while we collected many ‘transport current’ spikes. Thus it is most likely that these 0T spikes are ‘transport current’ spikes.

It is also interesting to notice that the number of spikes collected during the second current ramp right after a quench are significantly less than the number we observed for the first current ramp. This can lead us to a conclusion that the ‘transport current’ spikes are sensitive to strand magnetization.

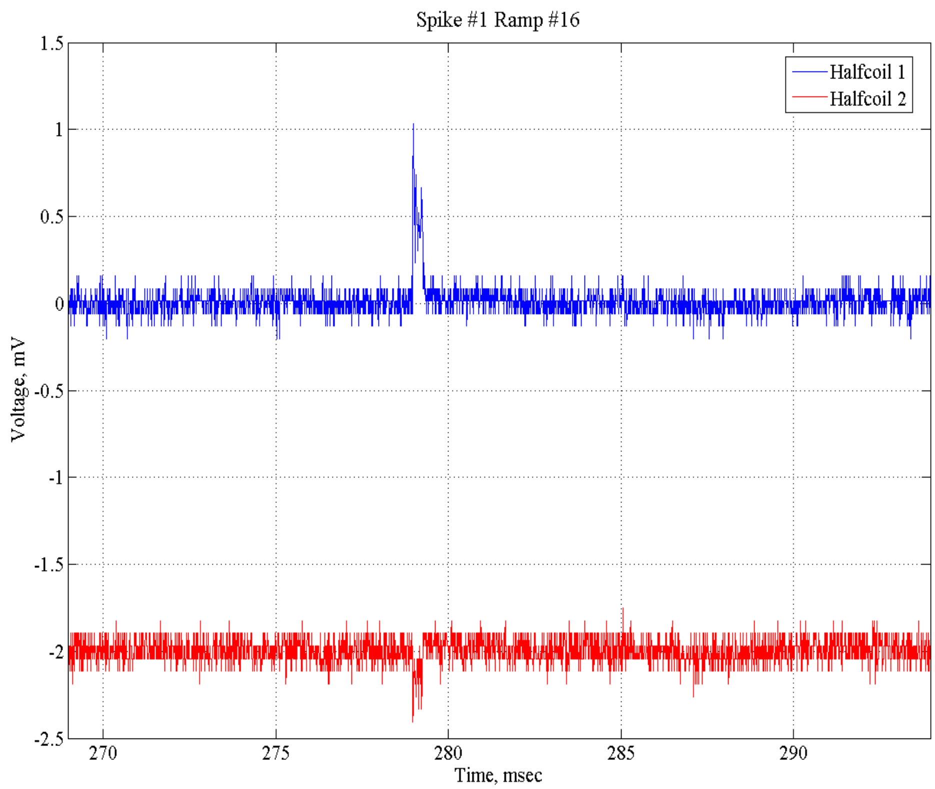

Fig. 8.1.1 V-I measurement 0T, sample positively magnetized

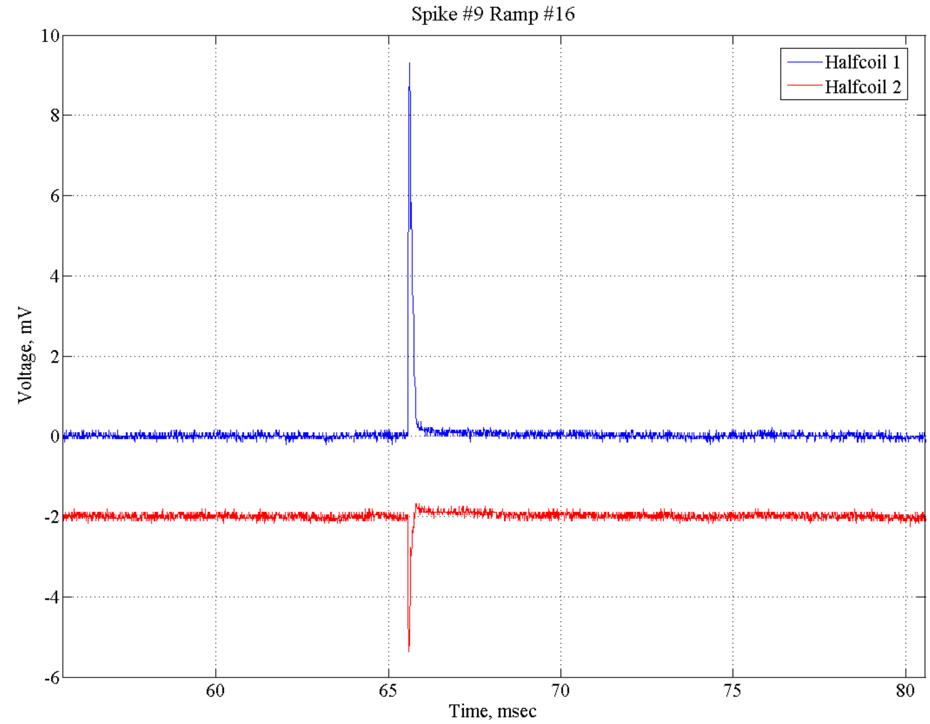

Fig. 8.1.2 V-I measurement 0T, sample positively magnetized

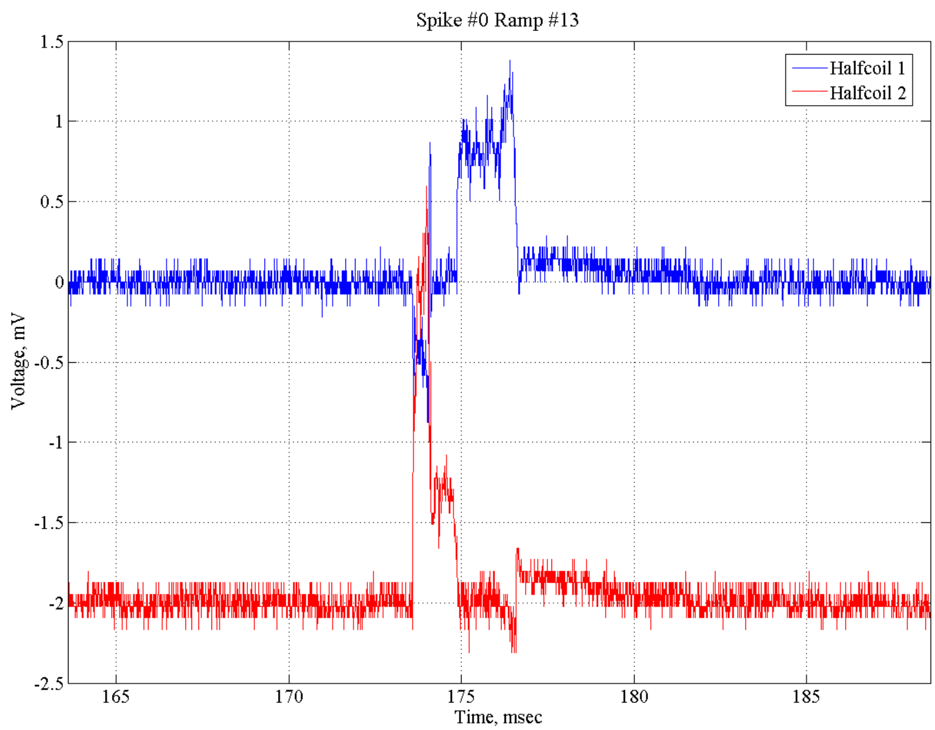

Fig. 8.1.3 V-I measurement 0T, sample positively magnetized

8.2) V-I measurements: field > 0 T and the sample was negatively magnetized

In these measurements (ramps 43, 45, 46, 47, 48, 49, 50, 52, 57) it has been observed only one ‘transport current’ spike, fig. 8.2.1, while the other spikes seemed to be ‘transport current’ spikes followed by high frequency oscillations, fig.8.2.2. Most of the time oscillations were in both halves of the coil. For ramp 57, at quite high field 8 T, it is not clearly seen that oscillations are preceded by a signal similar to ‘transport current’ spike, fig. 8.2.3.

It is also not clear why at 0T no oscillations were observed. The sign of the magnetization doesn’t seem to be related to oscillations because we were able to observe oscillations regardless what was the sign of the magnetization (see ramp 10 at 9T as an example for ‘transport current’ spike followed by oscillations when the sample was positively magnetized fig. 8.2.4). A possible cause of oscillating signals could be mechanical motion.

8.3) V-I measurements: high field, sample magnetized and training

In ramp 2 the signal is just oscillating and it can occur either halves or only in one half of the coil, fig. 8.3.1-8.3.3. Comparing the FFT of the spike signal to that of the noise one can conclude that these fast oscillations have a frequency lower than 20 kHz, fig. 8.3.4-8.3.6

8.4) V-H measurements

In these measurements we observed all types of spikes identified: ‘propagating magnetization’ spikes fig. 8.4.1, ‘no propagating magnetization’ spikes fig. 8.4.2, ‘transport current’ spikes fig. 8.4.3 and mixed spikes.

It is interesting to notice that when a ‘mixed’ or a ‘propagating magnetization’ spike appeared, the magnetic field was higher than ~0.9T.

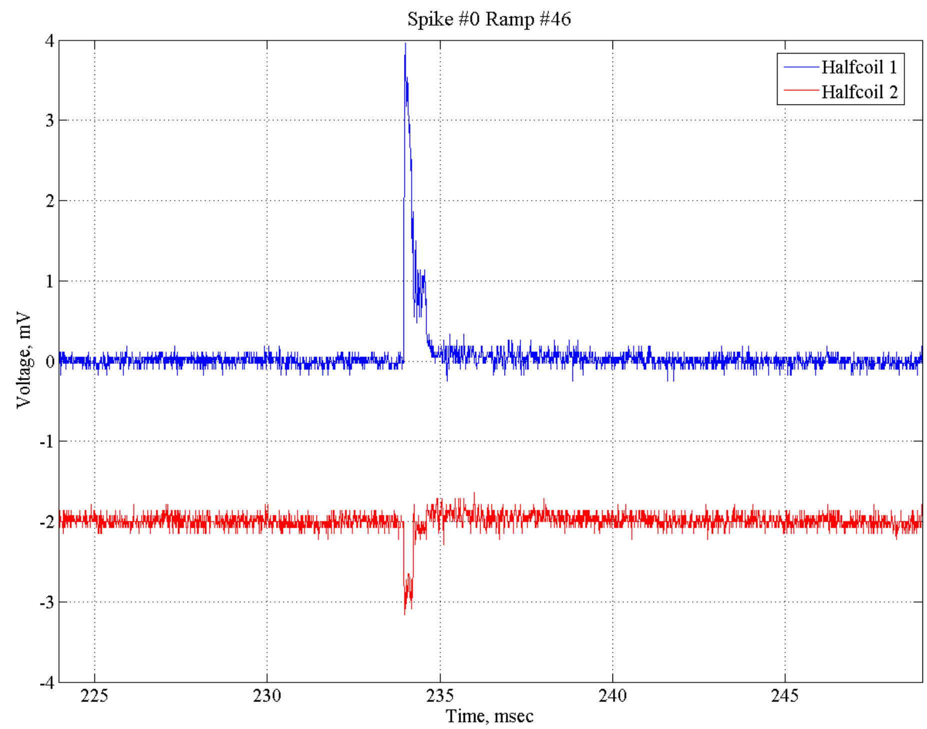

Fig. 8.2.1 V-I measurement field >0T, sample negatively magnetized

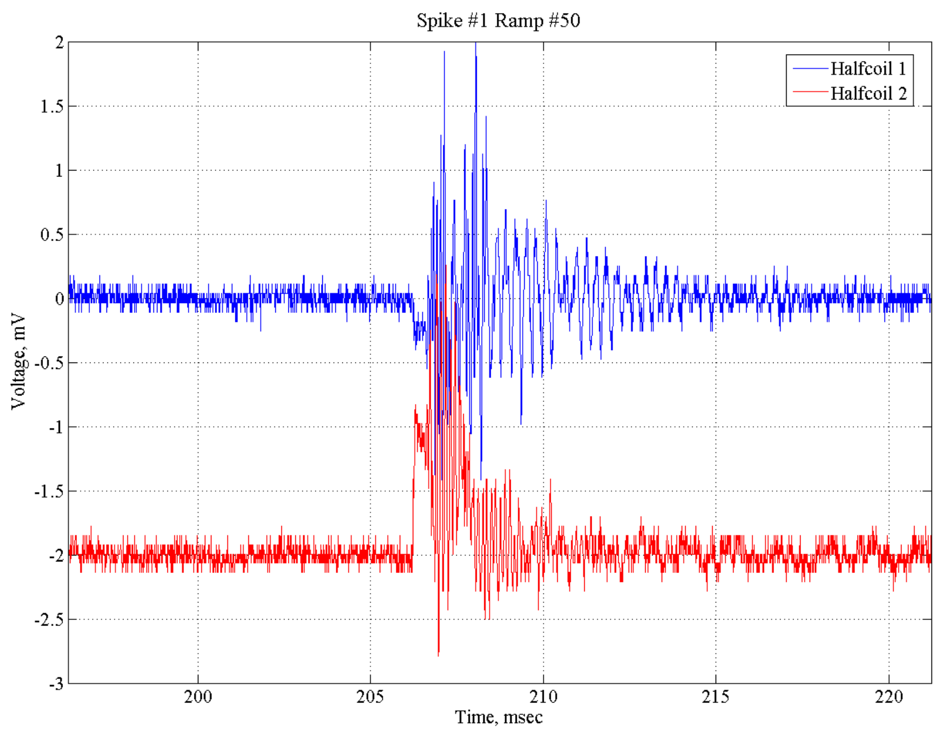

Fig. 8.2.2 V-I measurement field >0T, sample negatively magnetized

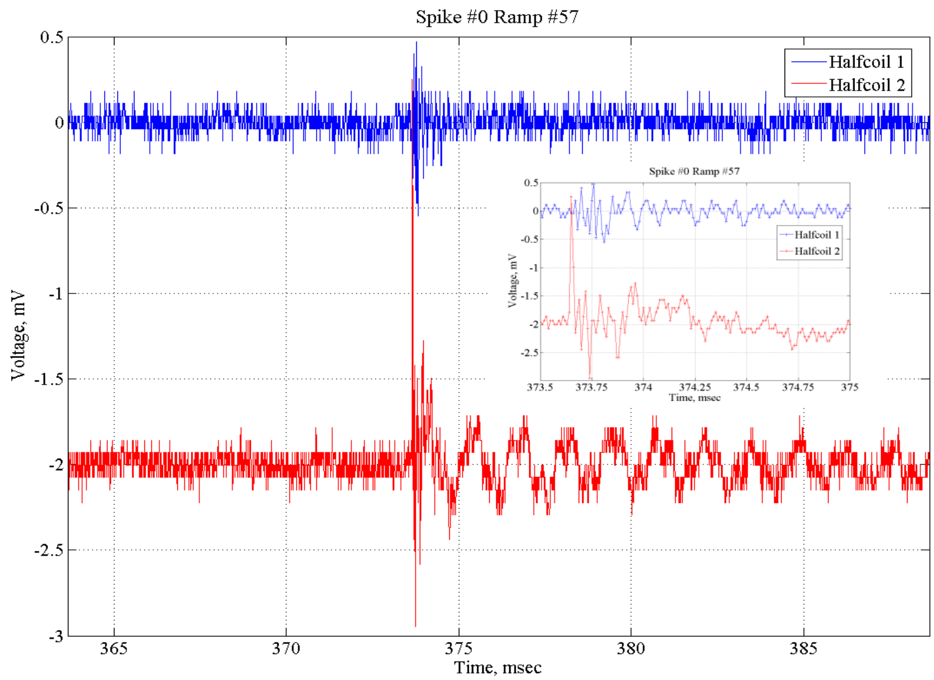

Fig. 8.2.3 V-I measurement field >0T, sample negatively magnetized

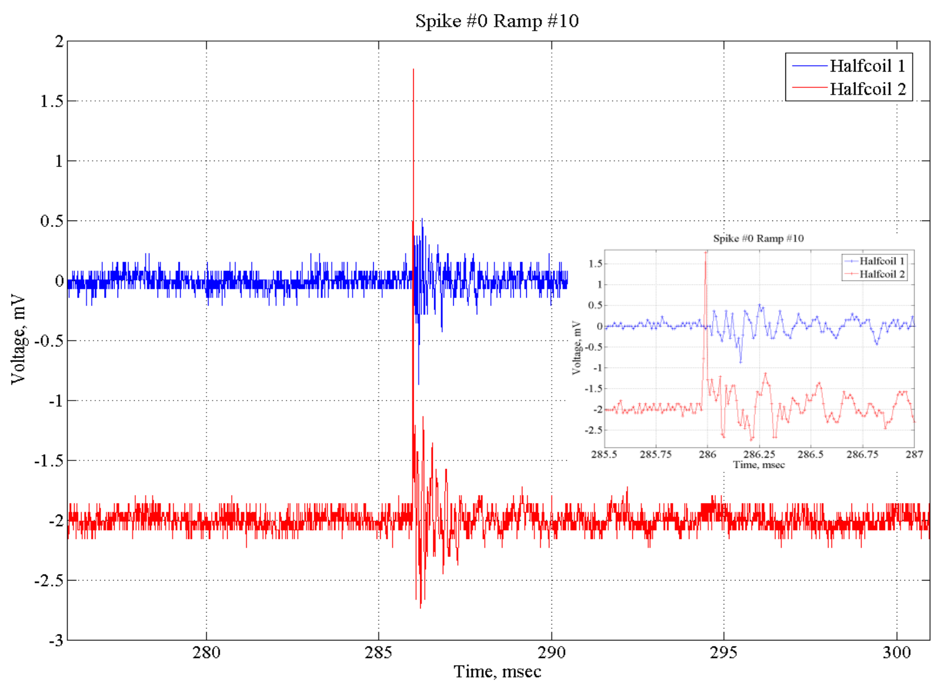

Fig. 8.2.4 V-I measurement field >0T, sample positively magnetized

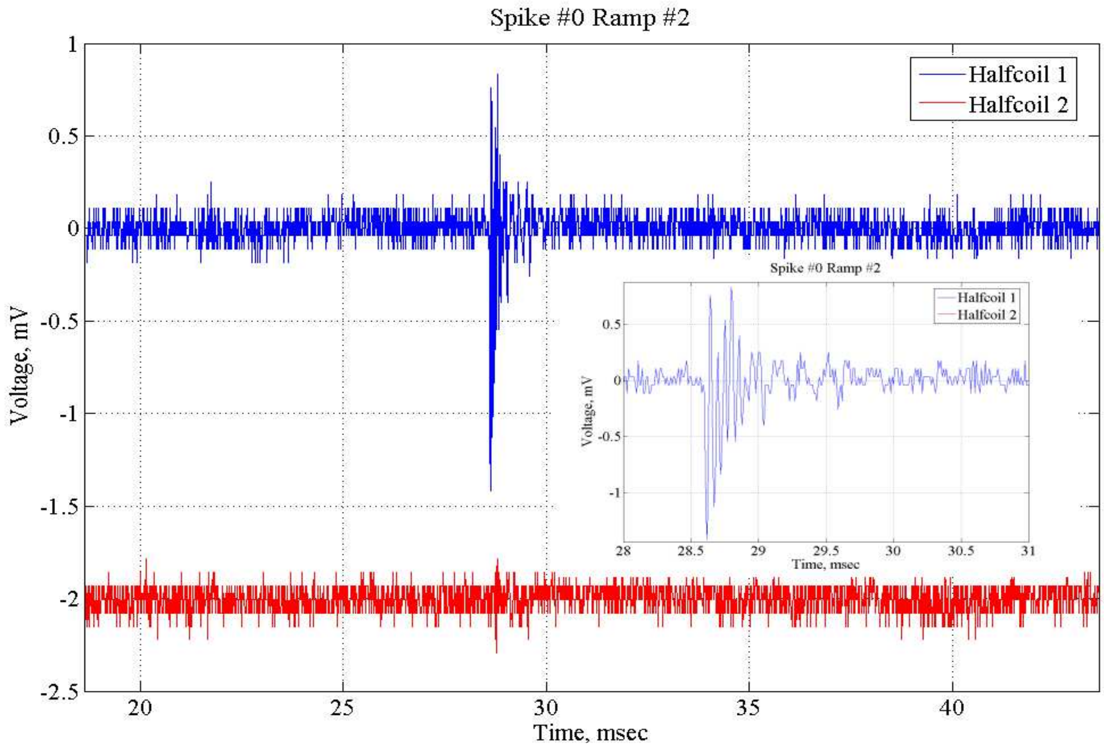

Fig. 8.3.1 V-I measurement high field, sample negatively magnetized, training

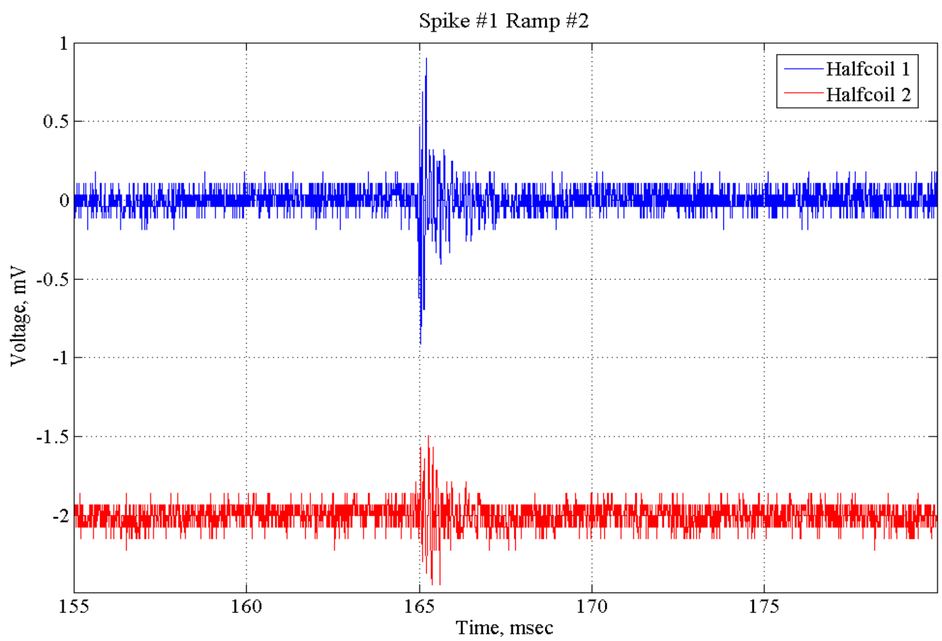

Fig. 8.3.2 V-I measurement high field, sample negatively magnetized, training

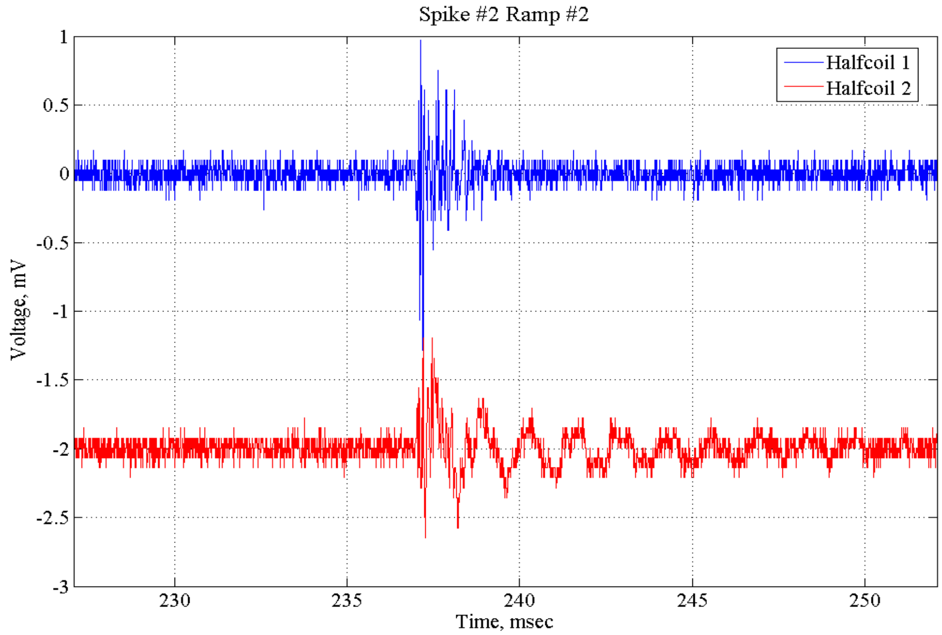

Fig. 8.3.3 V-I measurement high field, sample negatively magnetized, training

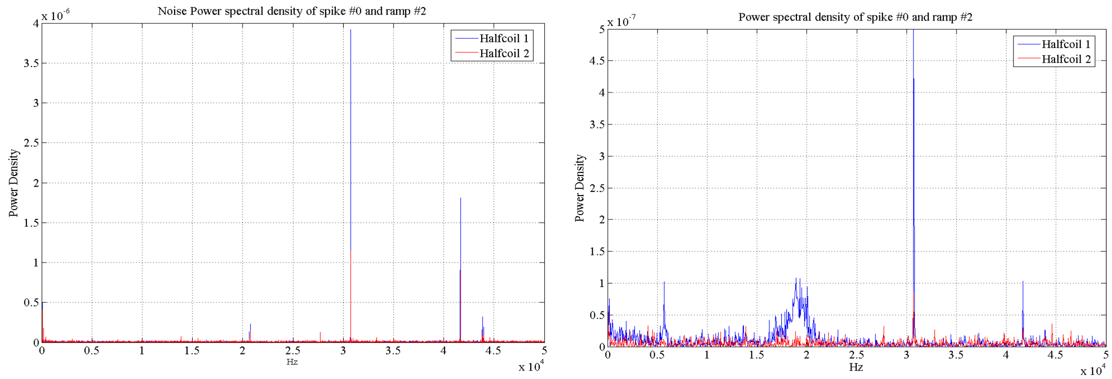

Fig. 8.3.4 FFT of the noise and of the voltage spikes showed in fig. 8.3.1

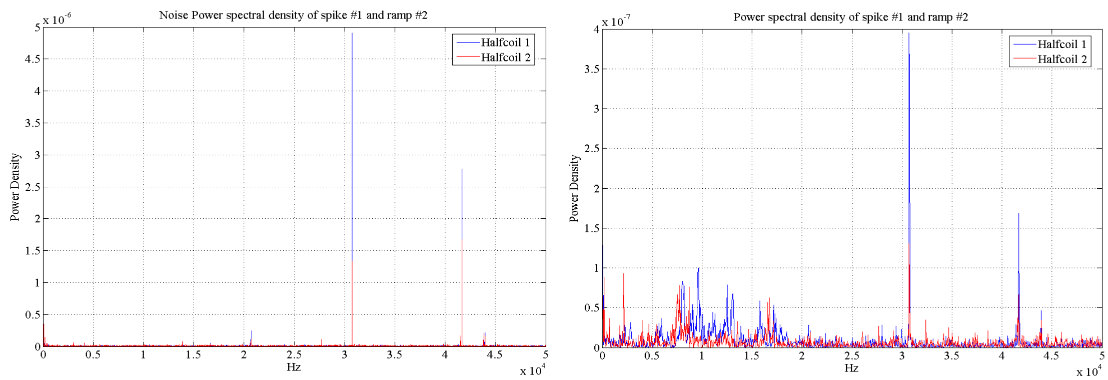

Fig. 8.3.5 FFT of the noise and of the voltage spikes showed in fig. 8.3.2

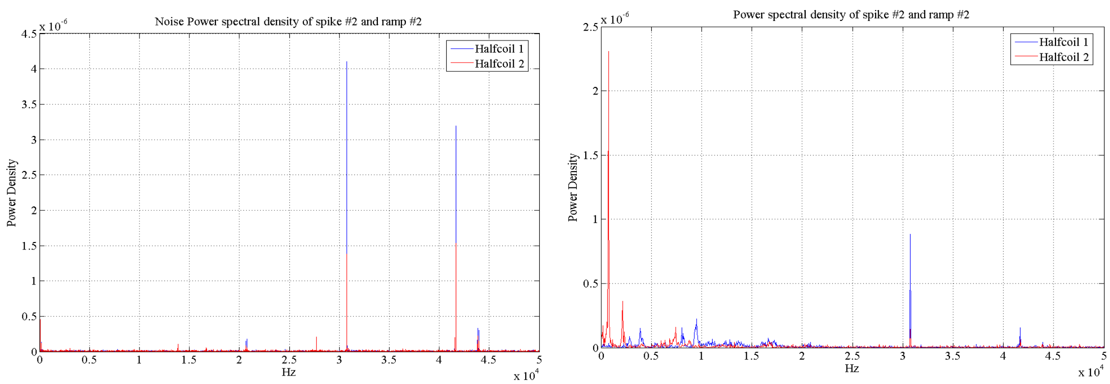

Fig. 8.3.6 FFT of the noise and of the voltage spikes showed in fig. 8.3.3

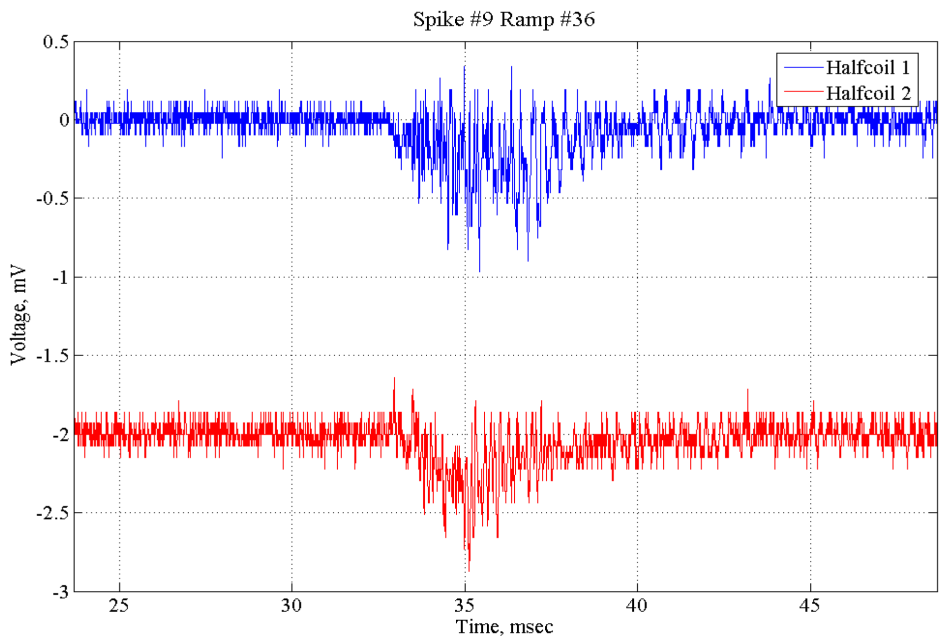

Fig. 8.4.1 V-H measurement with transport current: propagating magnetization spike

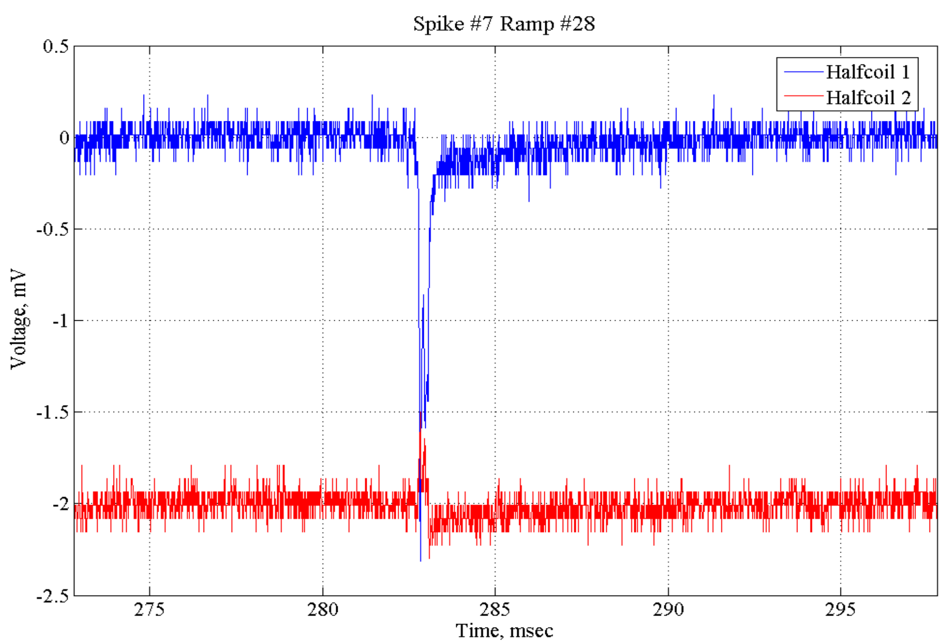

Fig. 8.4.2 V-H measurement with transport current: not propagating magnetization spike

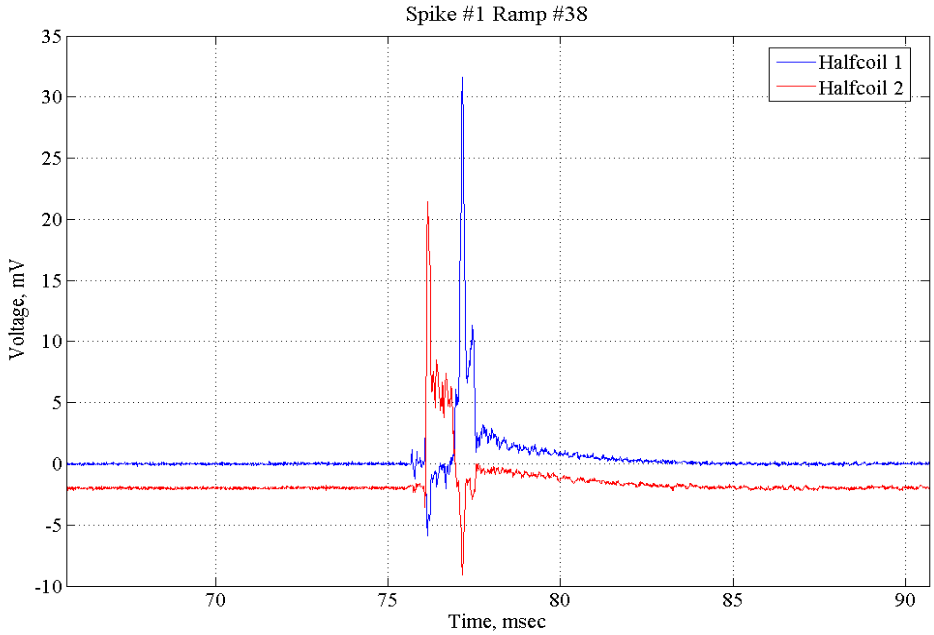

Fig. 8.4.3 V-H measurement with transport current: transport current spike

9) Quench Start

Using VSDS data we were able to determine the quench locations and whether the quench was triggered by a voltage spike. This information is summarized in the ninth column of tables 1, 2 and 3.

In the coil segment where the quench starts, the 'typical' voltage signal is positive and continuously increasing until the transport current does not decrease significantly.

9.1) Critical current measurements

The first quench signal recorded is shown in fig. 9.1.1. The blue and red lines represent the voltages in the two halves of the coil while the black and green lines the resistive voltages. The resistive voltage has been obtained by removing the inductive part of the voltage signal. Since the current signal, which was used to calculate the inductive voltage, was very noisy, the resistive voltage is much noisier than the raw voltage signal. In this particular ramp the quench occurred during the reversible transition of the superconductor. Since inductive signal appears before the start of the resistive voltage rise in the half coil 2 we can conclude that the quench has started in the splice (splice 2) and then it propagated into the coil region of the strand. All the quenches during critical current measurements between 15 and 9T have started in splice 2. At higher field and lower current values the time for the quench to propagate into the coil was longer and half coil 1 has never quenched.

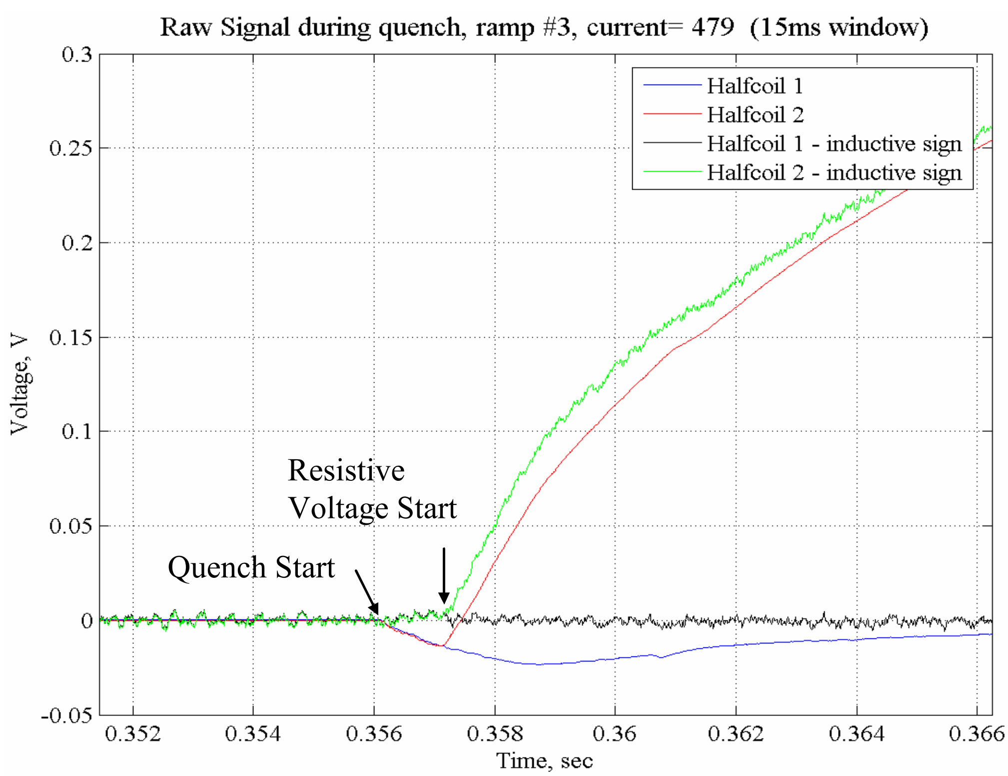

Fig. 9.1.1 V-I measurement 15T, quench

Fig. 9.1.2 shows the quench signal that occurred during the 12T critical current measurement. In this example the quench propagates from half coil 2 to half coil 1. Resistive voltage rise in half coil 2 starts 0.5 ms after the quench start, while it required

3.5 ms for the quench to reach half coil 1. Since the half coil length was about 0.5m the quench propagation velocity was approximately 143m/sec.
At 10 and 9 T the strand quenched before we were able to observe reversible transition. On the other hand the quench signal is similar to the previous quench signals.

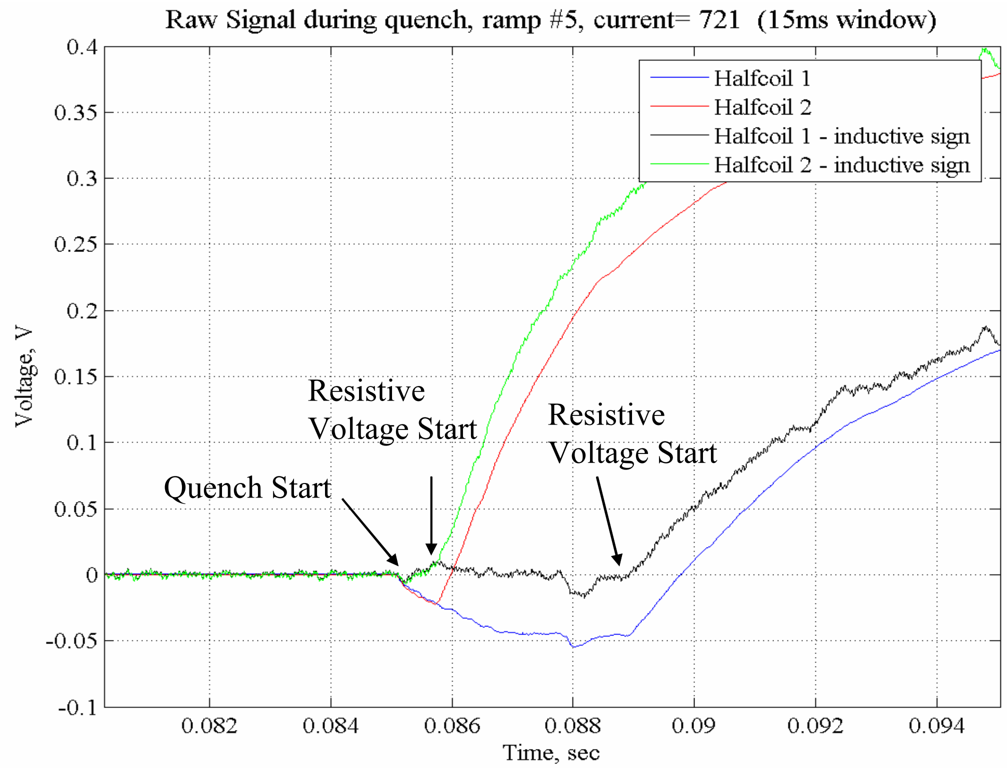

Fig. 9.1.2 1 V-I measurement 12T, quench

9.2) Quench Current much lower than the Critical Current

If quenches are preceded by a voltage spike the fast spike signal will modify the shape of the 'typical' quench signal.
A quench signal during V-I measurement at 0T is shown in fig. 9.2.1. In order to look for spikes only the raw voltage signal can be used since the resistive voltage is too noisy. The plot clearly shows that the quench, which occurs in half coil 1, is preceded by a 3 mV spike. The quench starts about 0.1 ms later.
Between ramp 13 and ramp 40, all the quenches had spikes right before the quench started but ramps 24 and 39. All the spikes were positive and there was no difference in signal shape between V-I and V-H tests fig. 9.2.2. It is interesting to notice that if the transport current was higher than 800A, spikes amplitude was in the order of no more than 5mV, while for quench currents of 650A and 700A spikes amplitudes were in the order of 25mV, fig. 9.2.3 and 9.2.4.

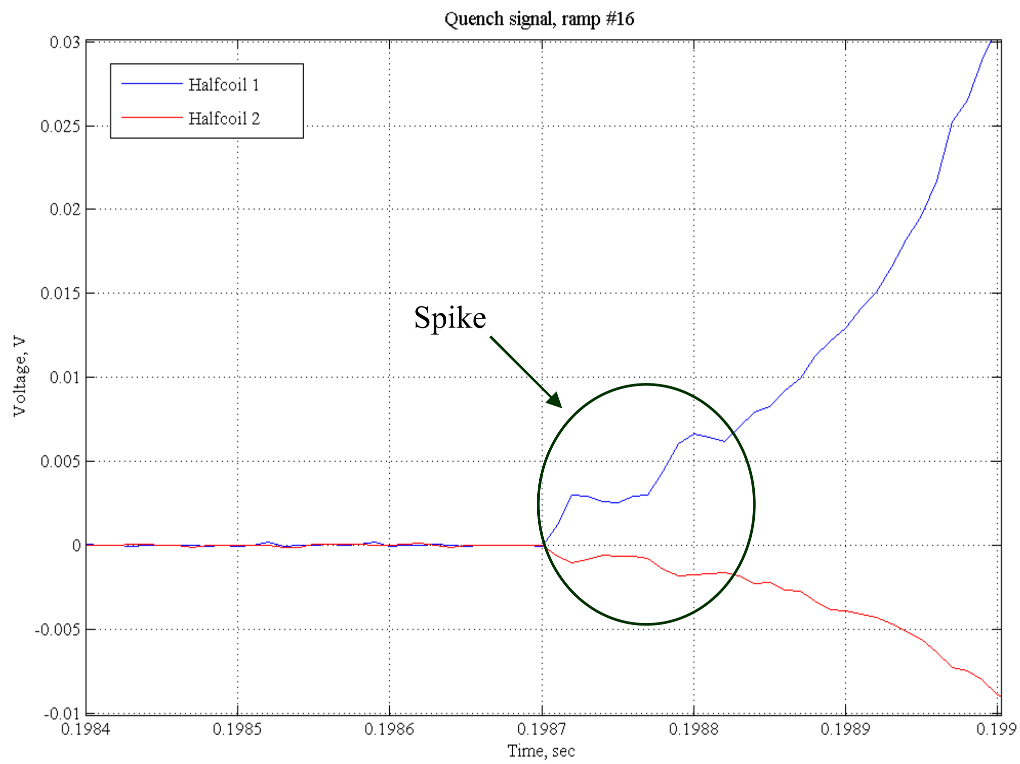

Fig. 9.2.1 Voltage spike preceding the quench while ramping the current

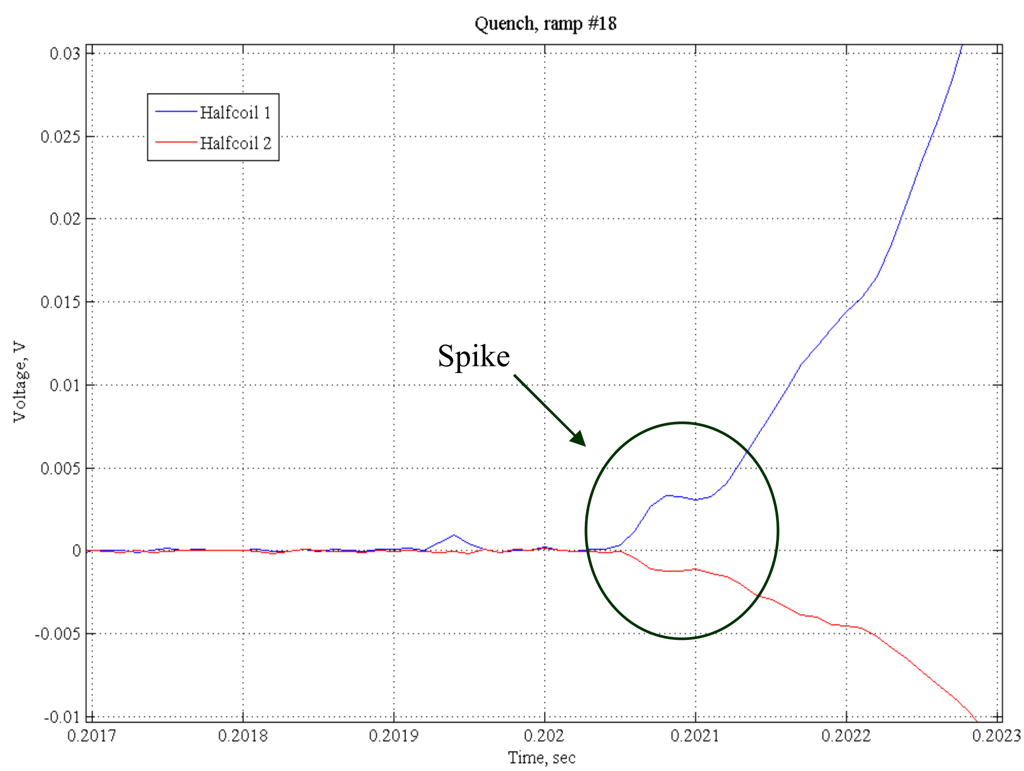

Fig. 9.2.2 Voltage spike preceding the quench while ramping the field

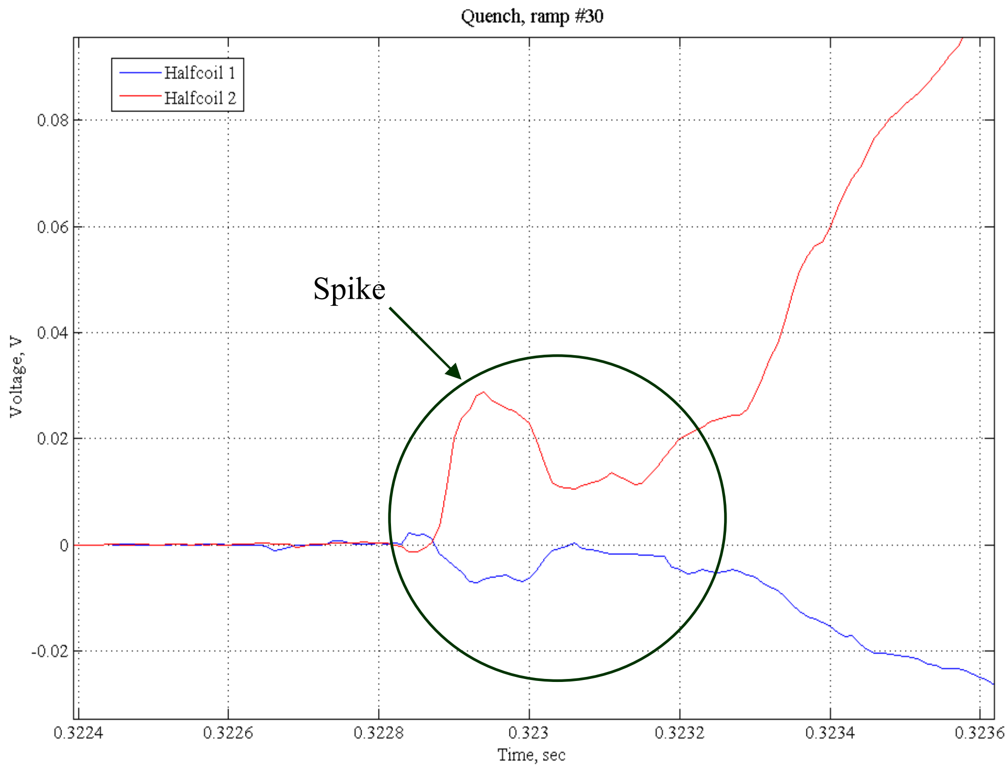

Fig. 9.2.3 Voltage spike preceding the quench while ramping the field, low current value

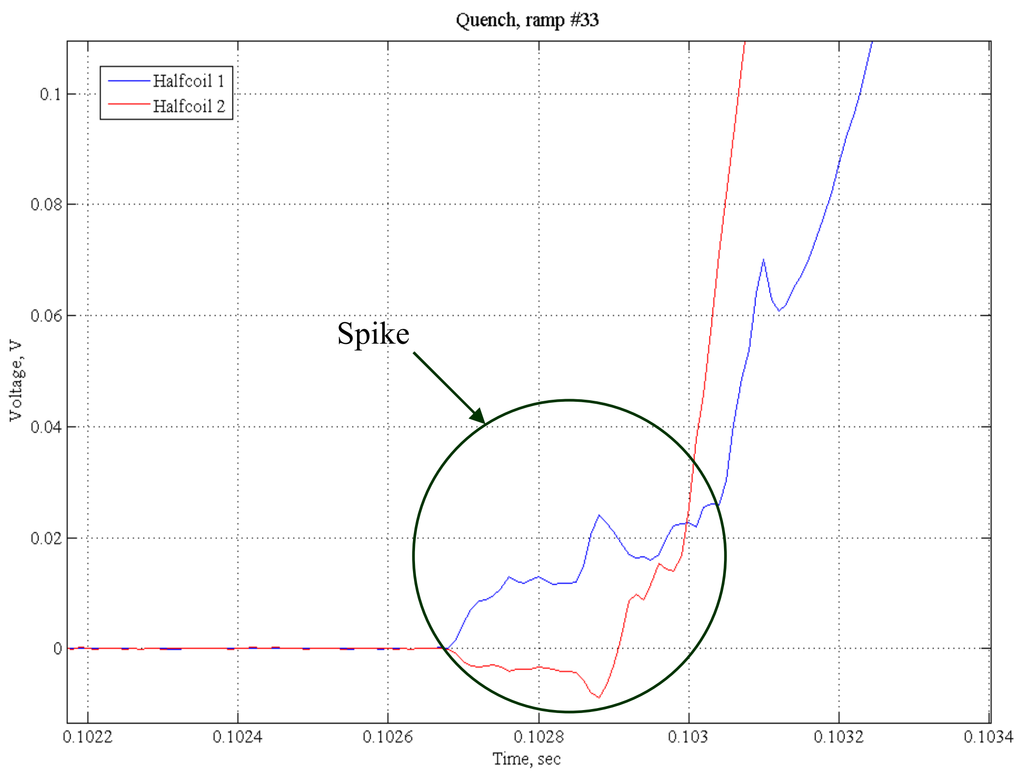

Fig. 9.2.4 Voltage spike preceding the quench while ramping the field, low current value

Between ramp 41 and 56 only 7 quenches out of 16 showed spikes, their shape was similar to shape of the previous ramps.
For ramps 57, 58 and 59 the quench voltage signals were similar but completely different from all the other quench signals. In fig. 9.2.5 one of these quenches is shown. At the quench start the half coil 1 voltage signal decreased while the other half had a slightly positive rise. This voltage behavior can not be explained by sudden current decrease caused by power supply.

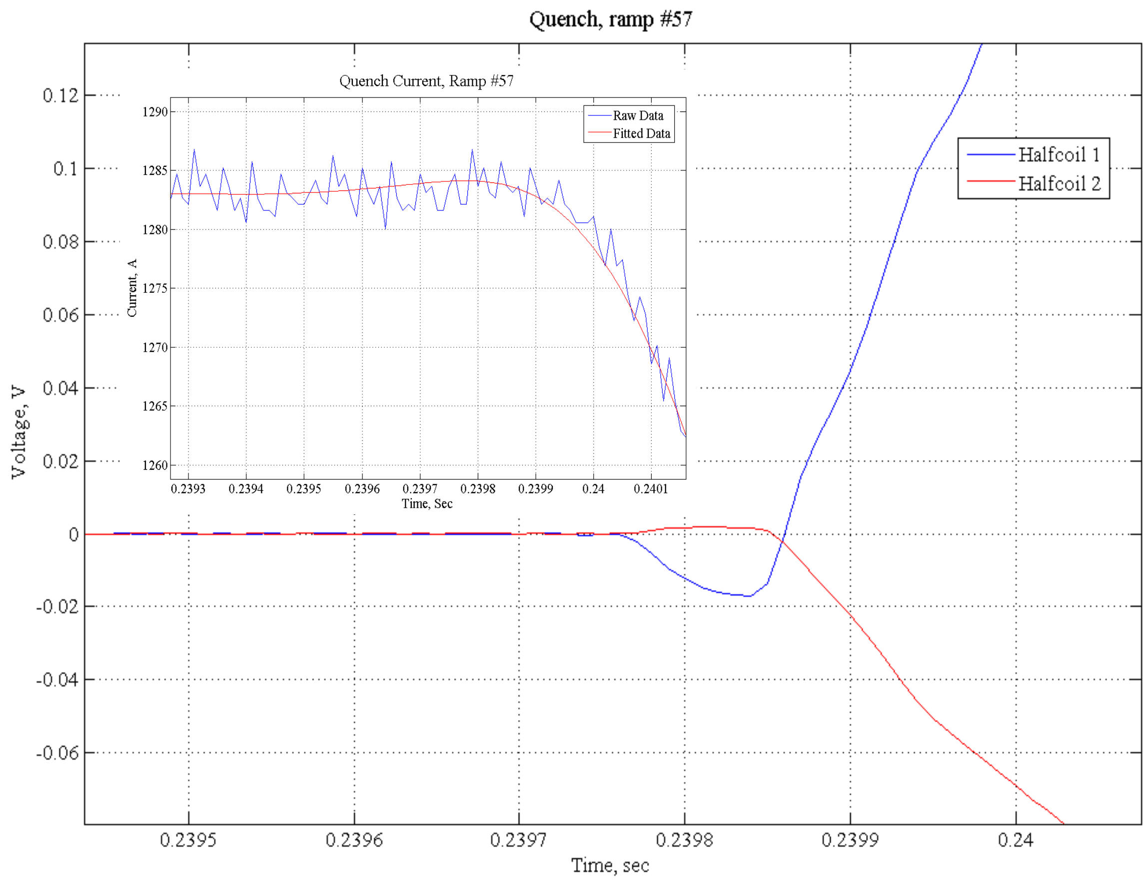

Fig. 9.2.5 1 V-I measurement 8T, quench

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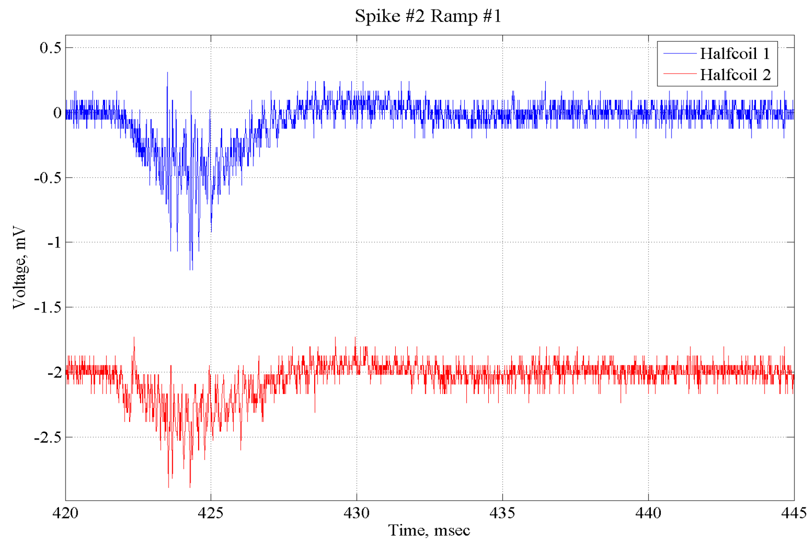
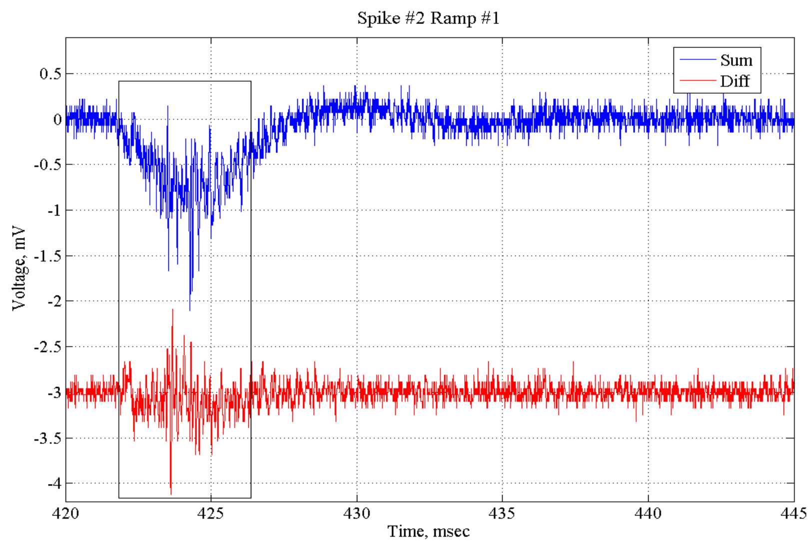
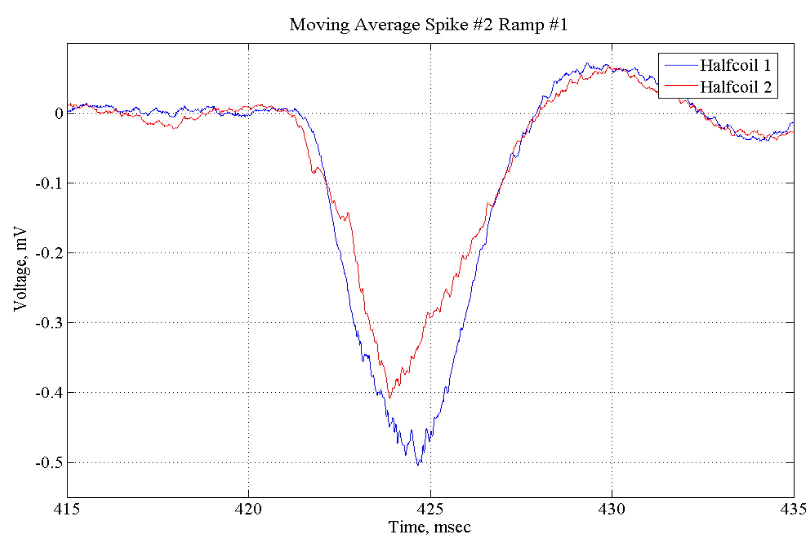
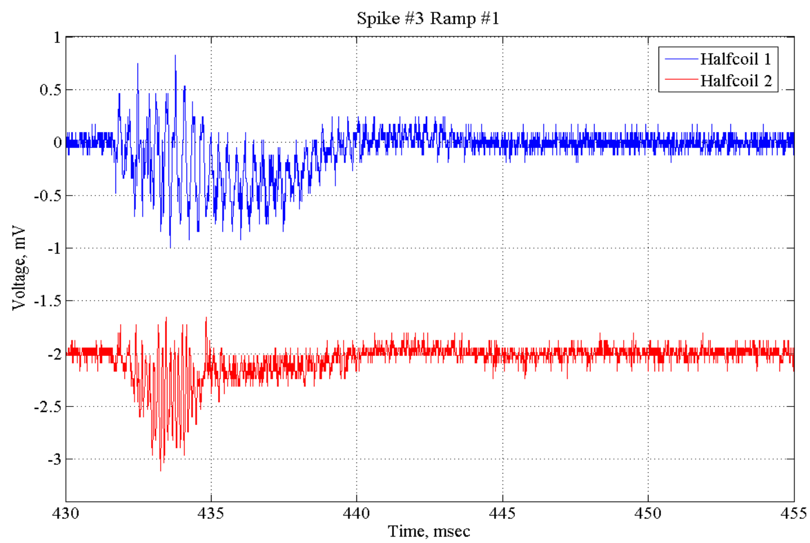
APPENDIX A –GLOBAL MAGNETIZATION SPIKES








Spike #3 Ramp #1
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
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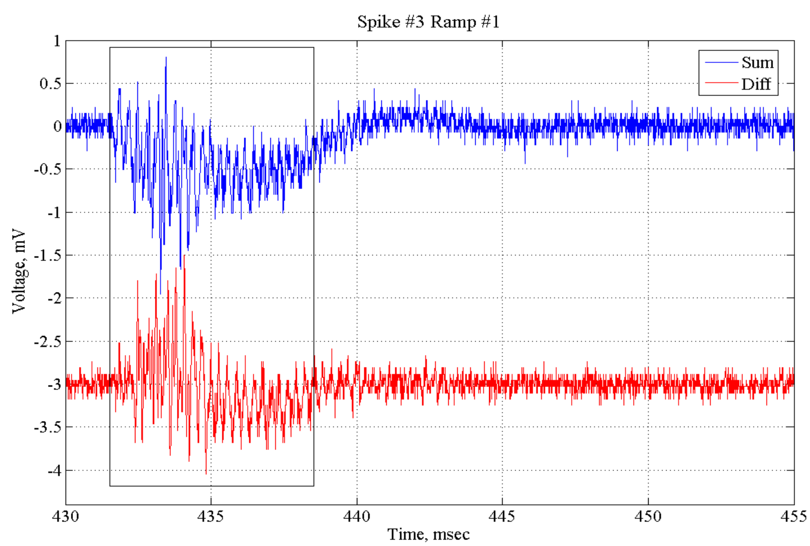
0
-0.5
-1
-1.5
-2
-2.5
-3
430
435
440
445
450
455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Sum
Diff
Voltage, mV
Time, msec
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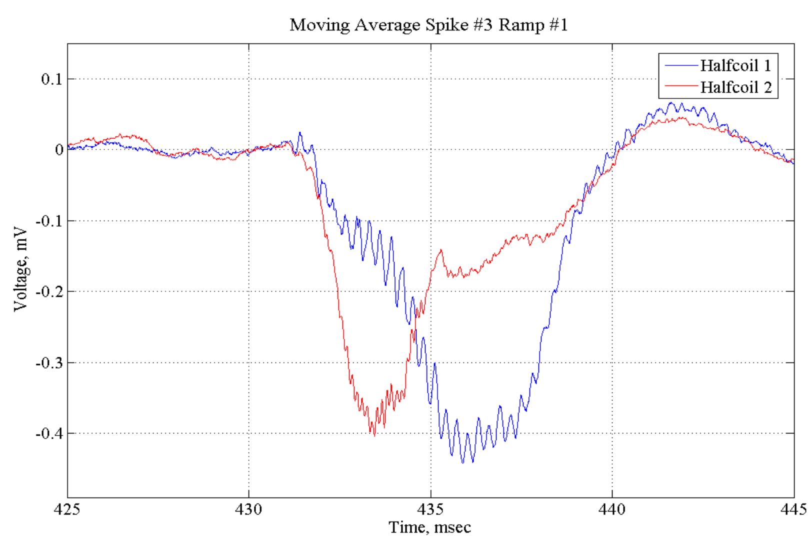
-3
-3.5
-4
430
435
440
445
450
455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Halfcoil 2
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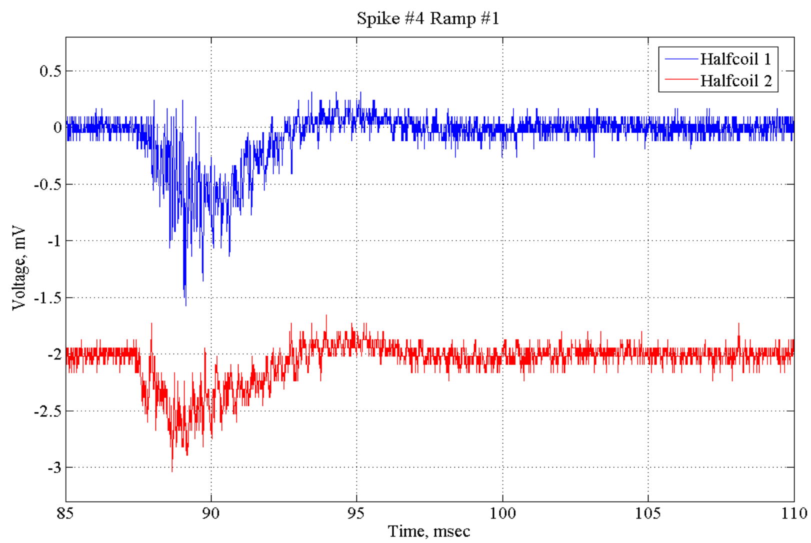
-0.4
425
430
435
440
445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Halfcoil 2
Voltage, mV
Time, msec
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-2
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-3
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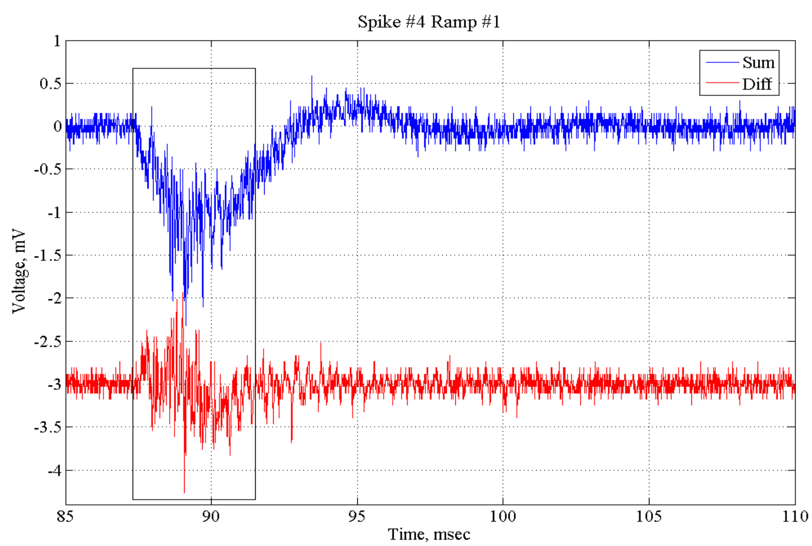
90
95
100
105
110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Diff
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Time, msec
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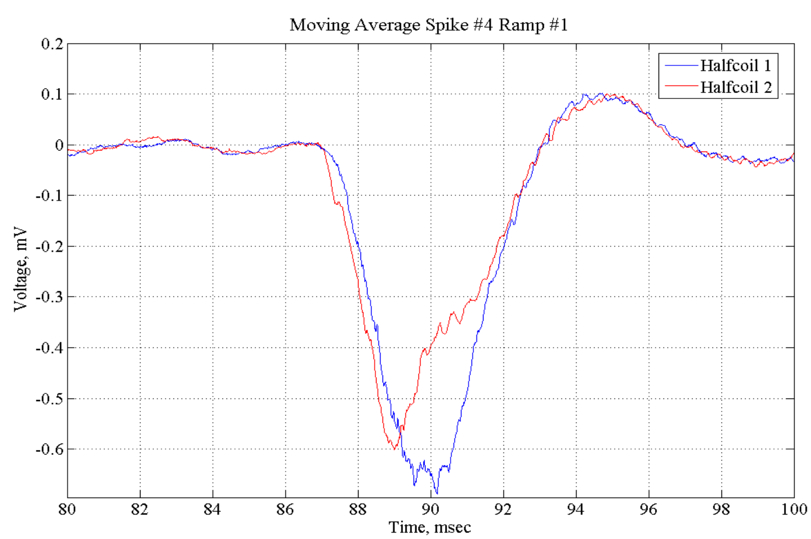
-4
85
90
95
100
105
110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Halfcoil 2
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82
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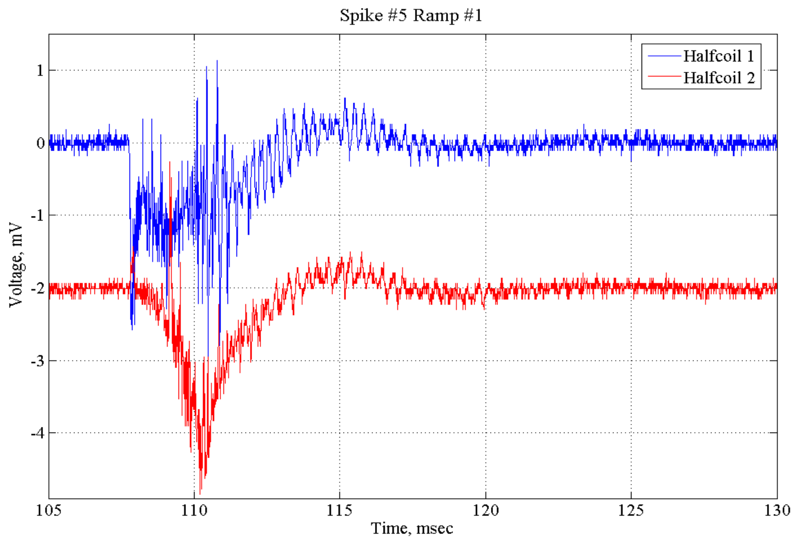
86
88
90
92
94
96
98
100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Time, msec
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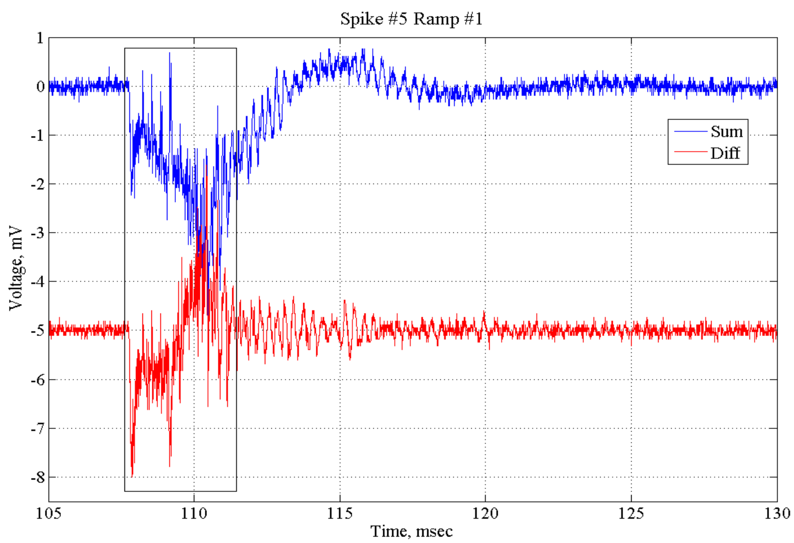
110
115
120
125
130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Diff
Voltage, mV
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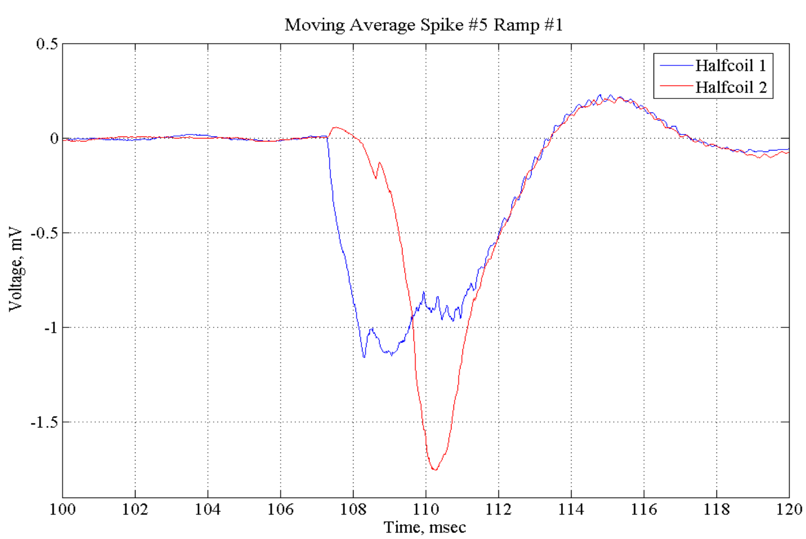
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Halfcoil 2
Voltage, mV
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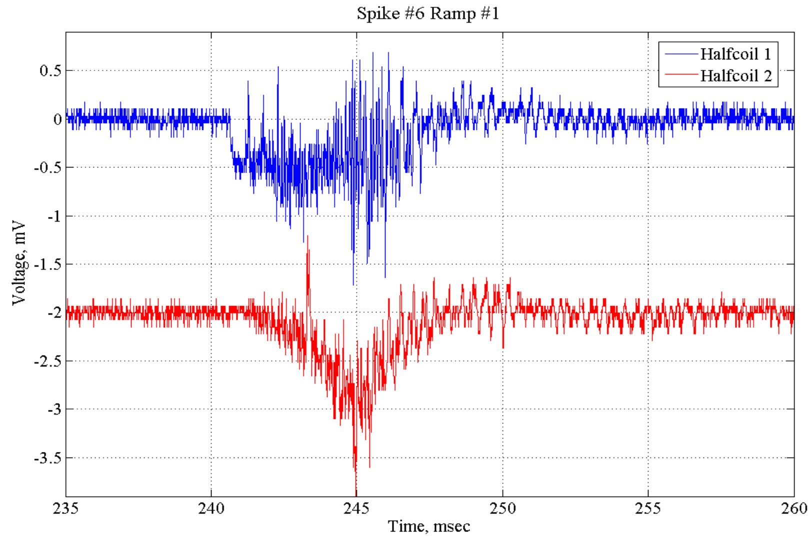
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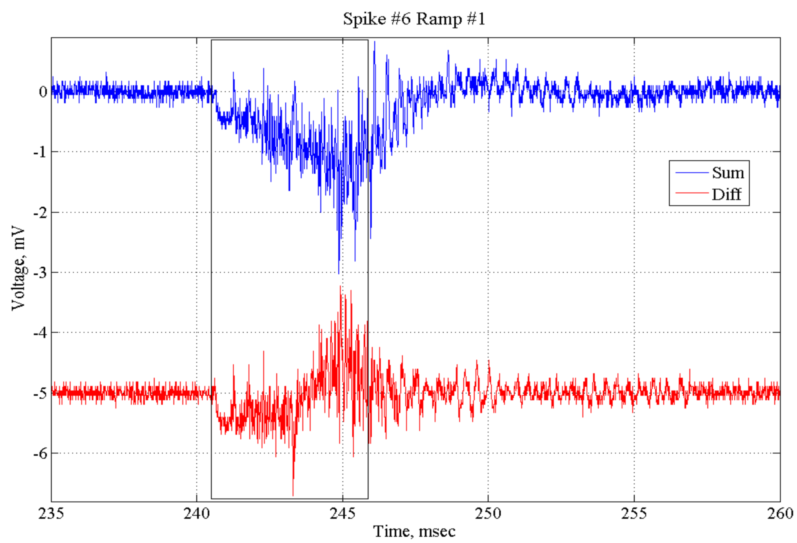
Voltage, mV
Time, msec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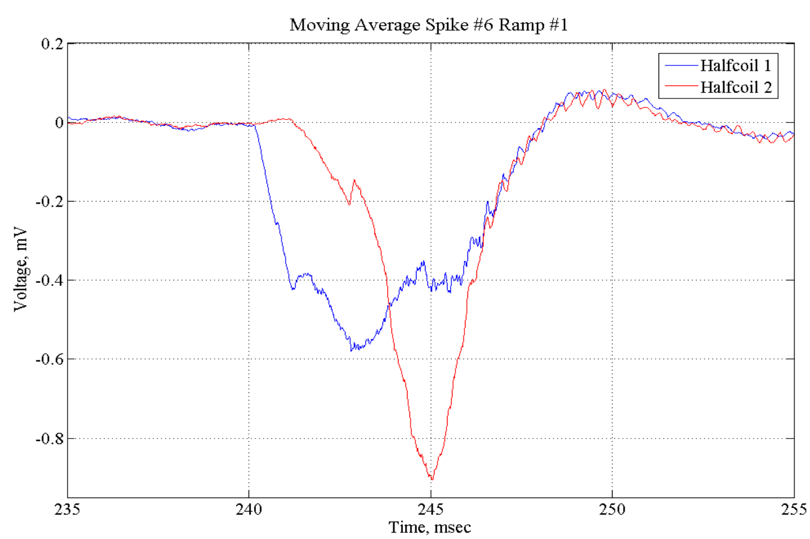
Diff
Voltage, mV
Time, msec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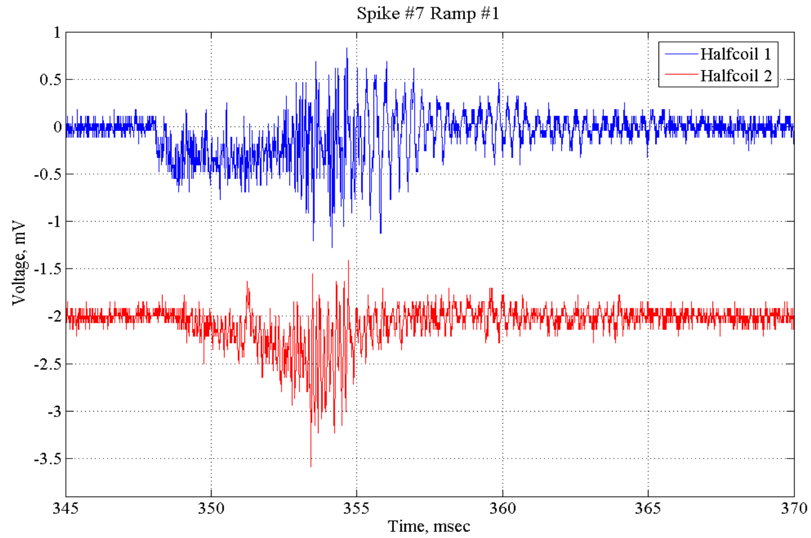
Time, msec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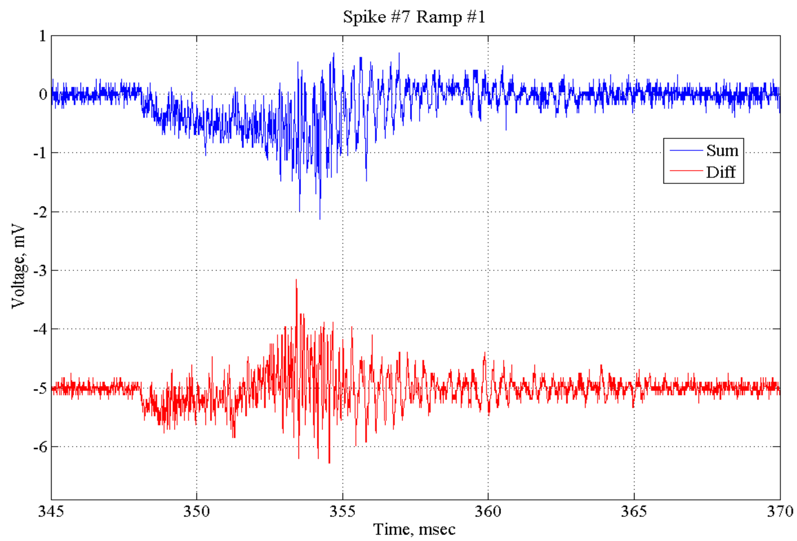
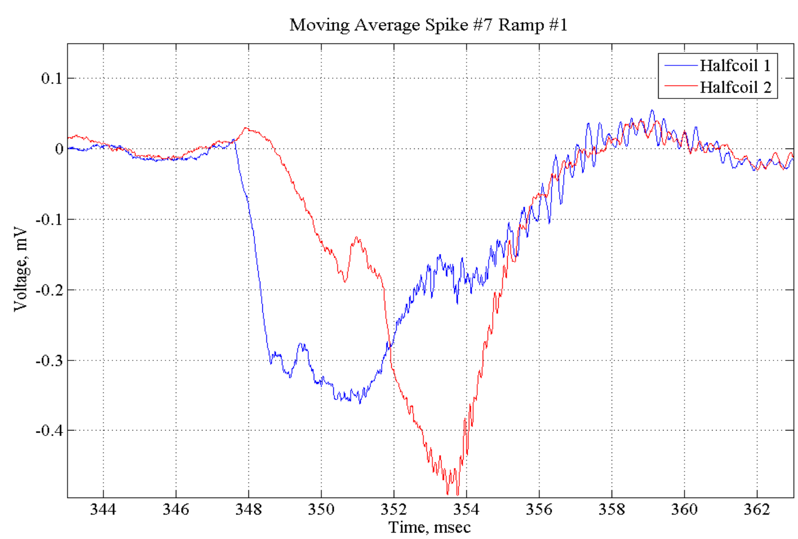
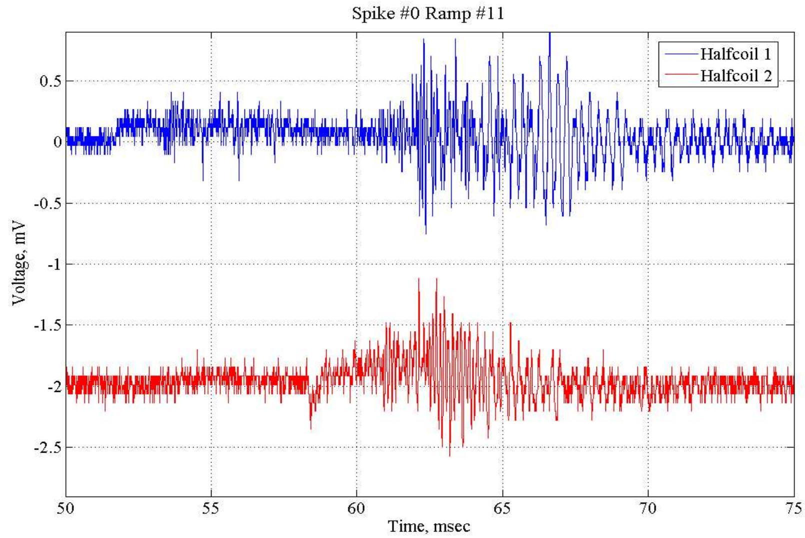
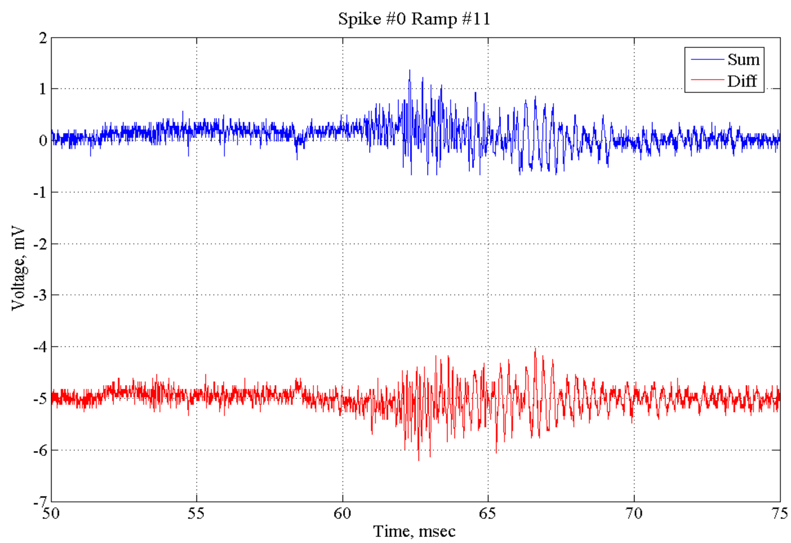
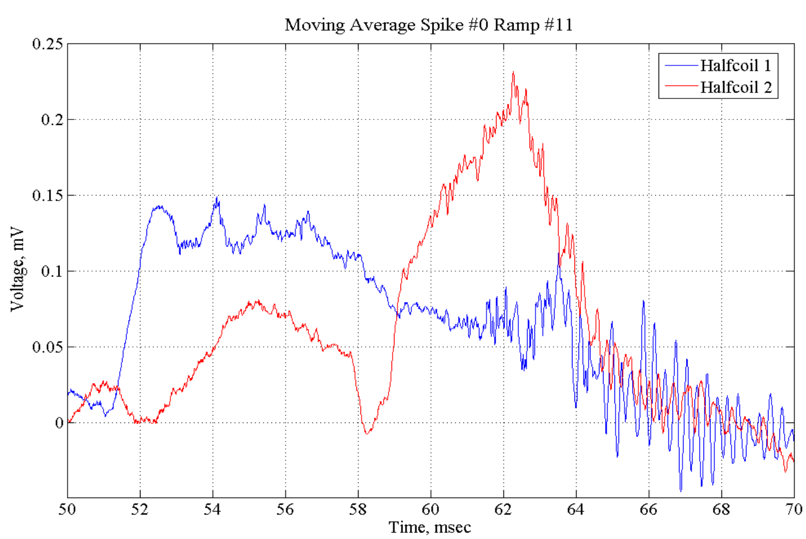
-2
-2.5
-3
-3.5
345
350
355
360
365
370

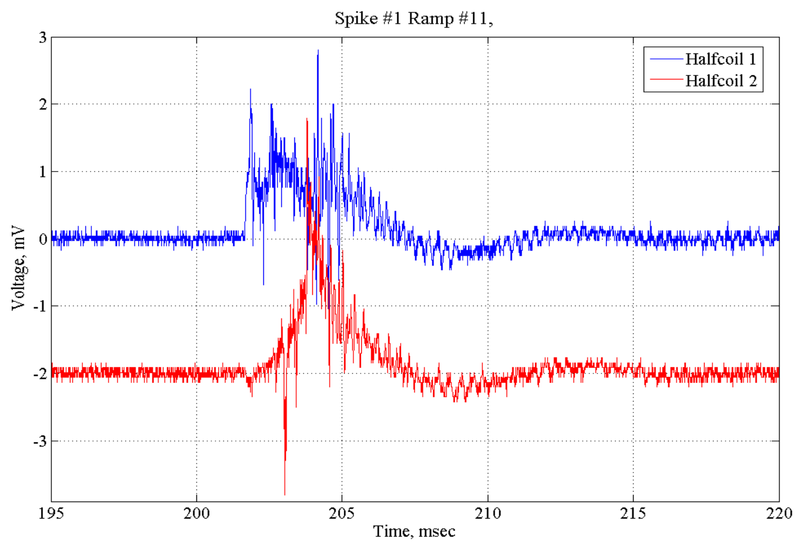

Spike #7 Ramp #1
Sum
Diff
Voltage, mV
Time, msec
1
0
-1
-2
-3
-4
-5
-6
345
350
355
360
365
370

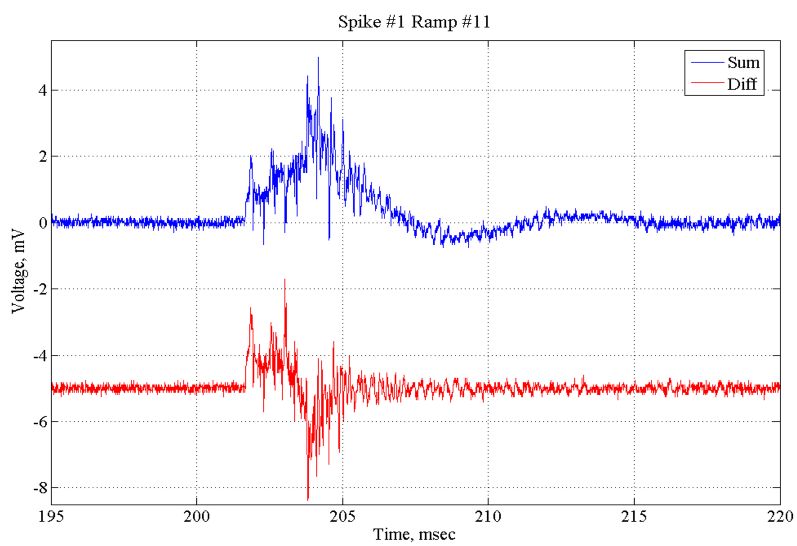

Moving Average Spike #7 Ramp #1
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.1
0
-0.1
-0.2
-0.3
-0.4
344
346
348
350
352
354
356
358
360
362

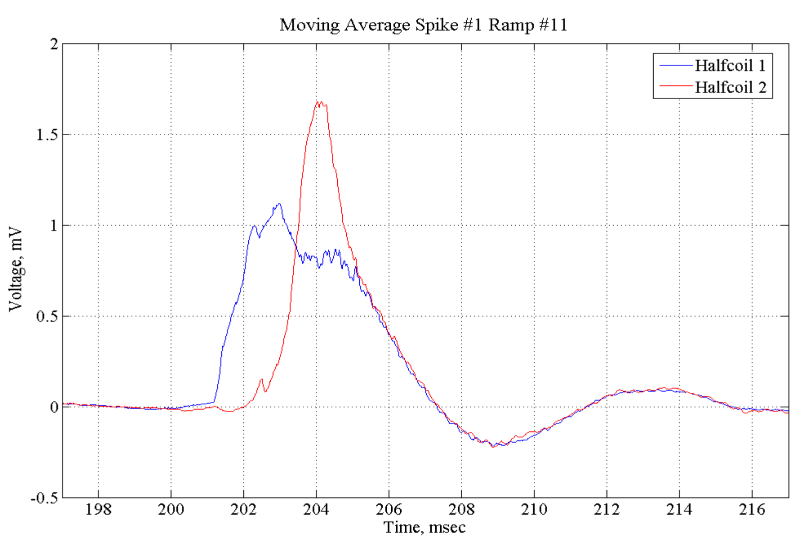

Spike #0 Ramp #11
Halfcoil 1
Halfcoil 2
0.5
0
-0.5
-1
-1.5
-2
-2.5
Voltage, mV
50
55
60
65
70
75
Time, msec

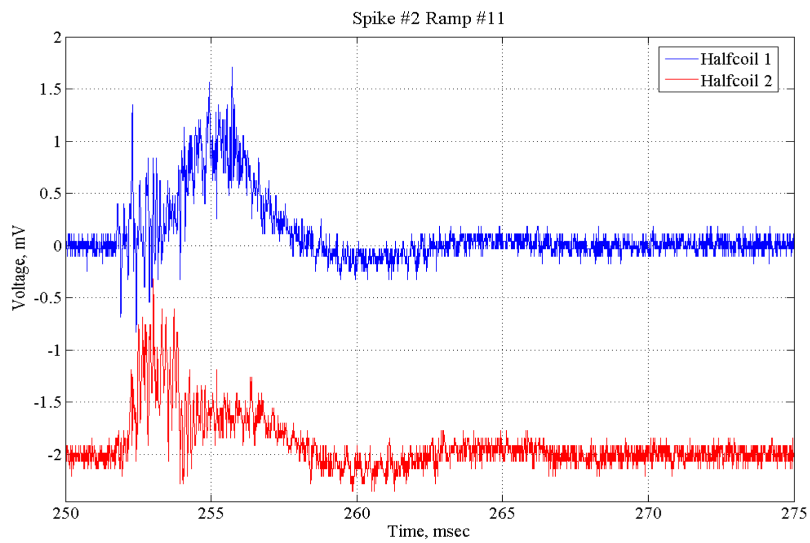

Spike #0 Ramp #11
Sum
Diff
2
1
0
-1
-2
-3
-4
-5
-6
-7
Voltage, mV
50
55
60
65
70
75
Time, msec

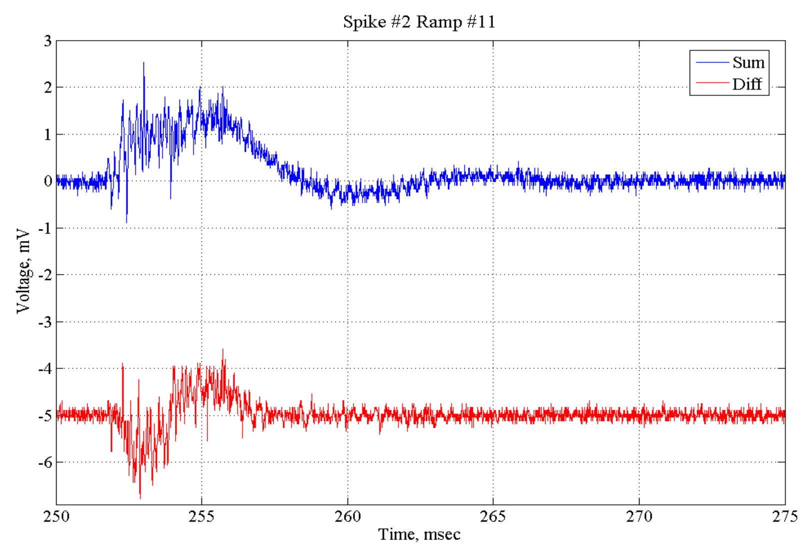

Moving Average Spike #0 Ramp #11
Halfcoil 1
Halfcoil 2
0.25
0.2
0.15
0.1
0.05
0
Voltage, mV
50
52
54
56
58
60
62
64
66
68
70
Time, msec

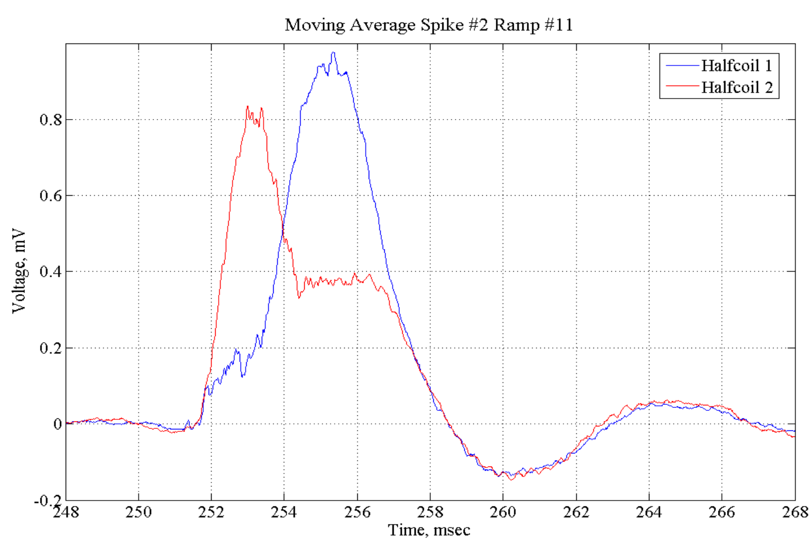

Spike #1 Ramp #11,
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

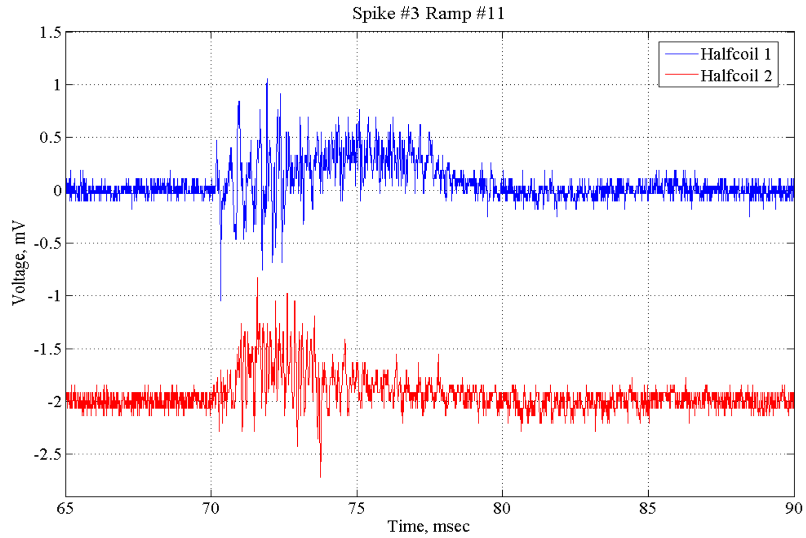

Spike #1 Ramp #11
Sum
Diff
Voltage, mV
Time, msec

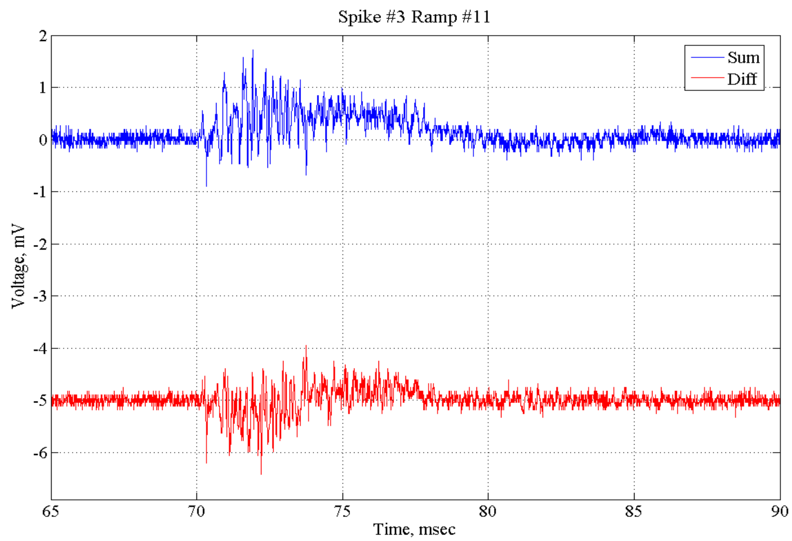

Moving Average Spike #1 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

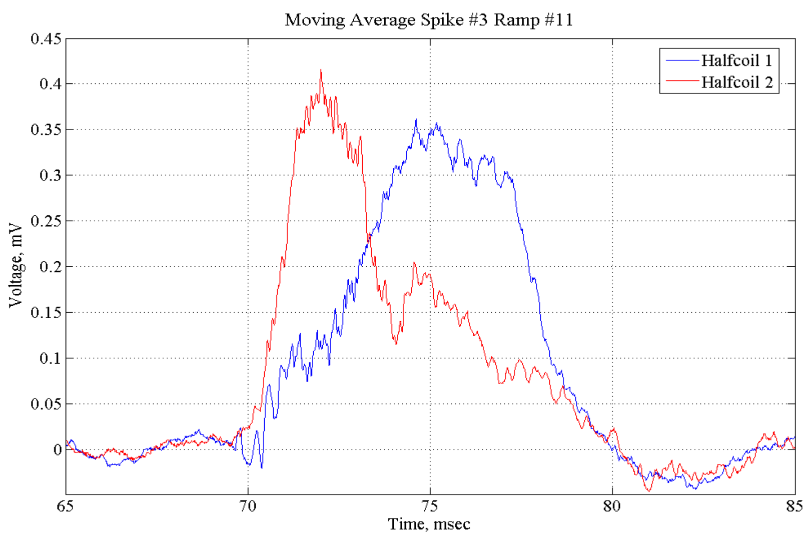

Spike #2 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

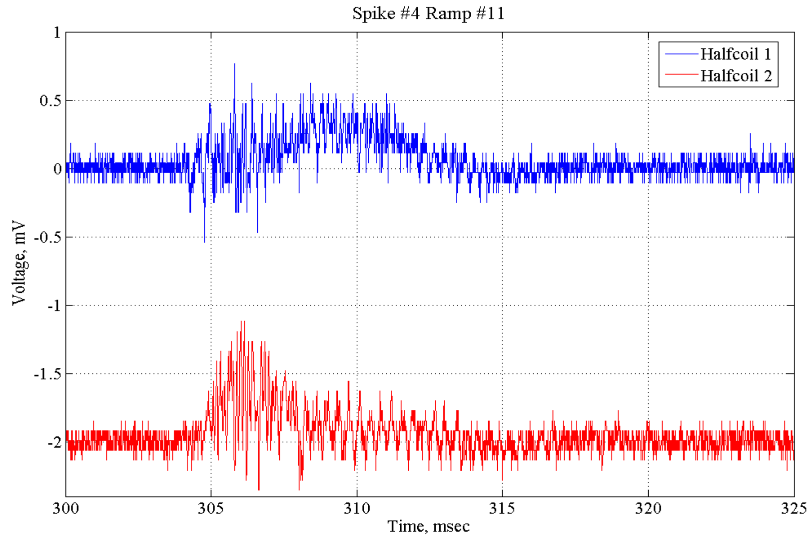

Spike #2 Ramp #11
Sum
Diff
Voltage, mV
Time, msec

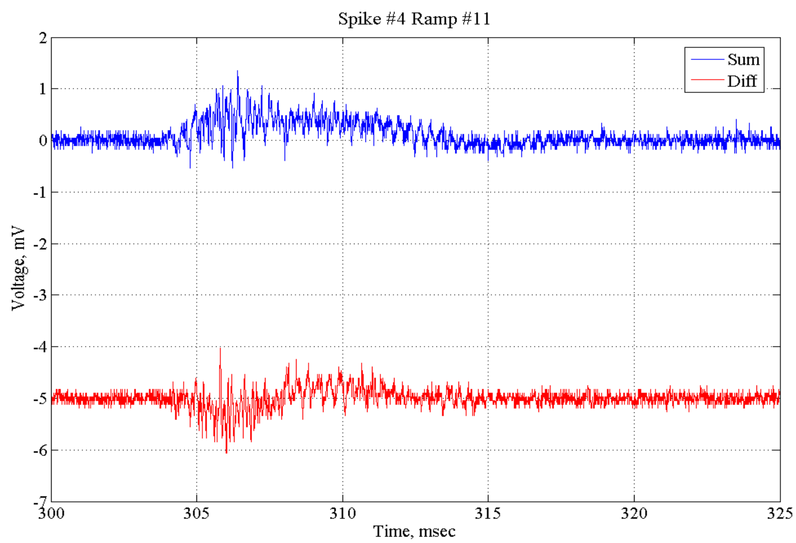

Moving Average Spike #2 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

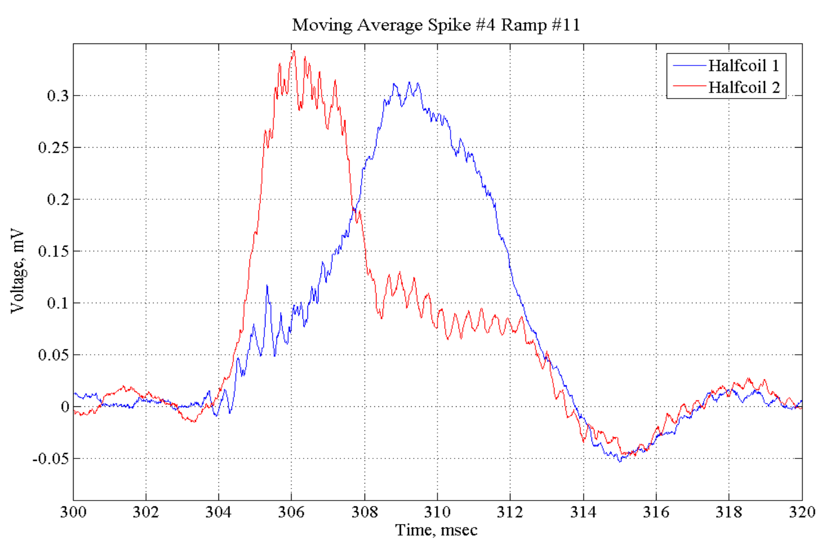

Spike #3 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
65
70
75
80
85
90

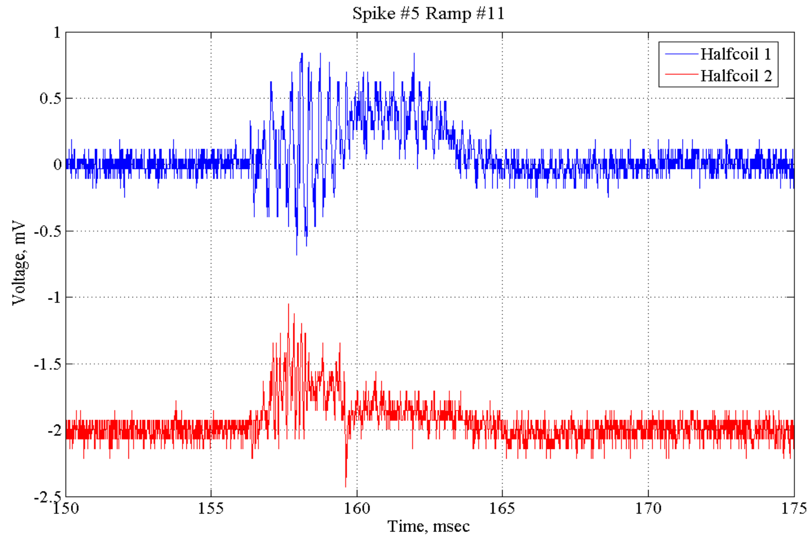

Spike #3 Ramp #11
Sum
Diff
Voltage, mV
Time, msec
2
1
0
-1
-2
-3
-4
-5
-6
65
70
75
80
85
90

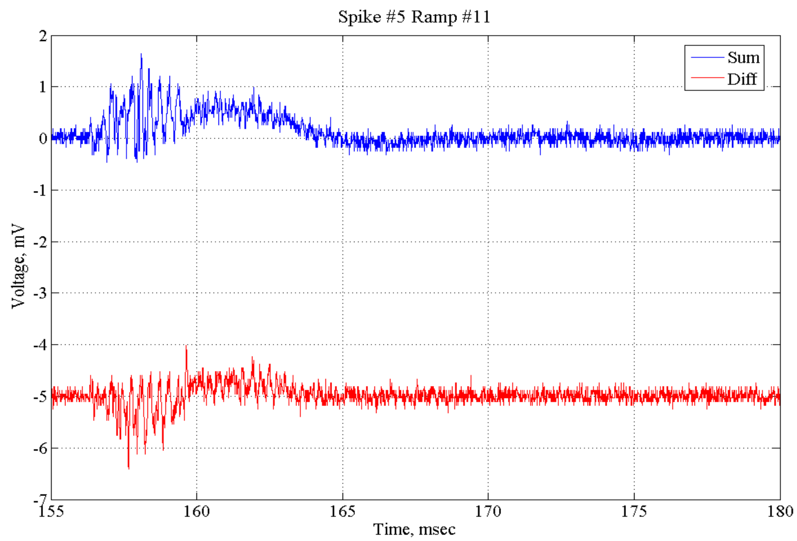

Moving Average Spike #3 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
65
70
75
80
85

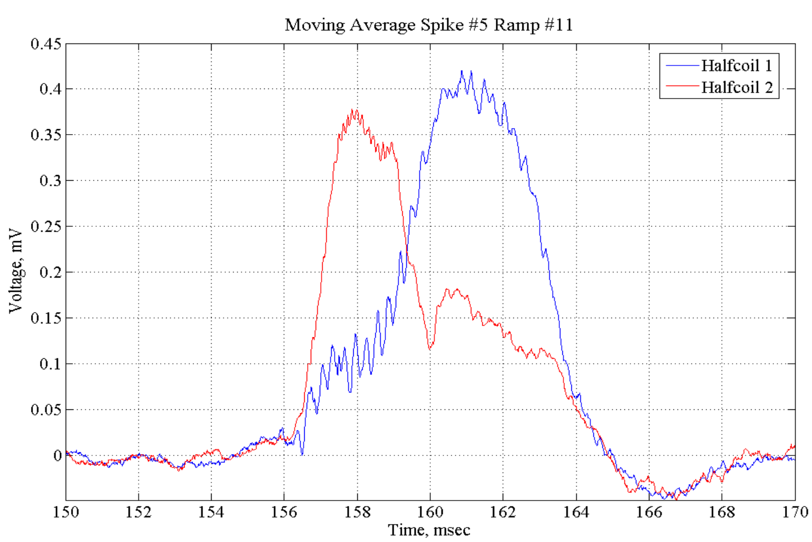

Spike #4 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

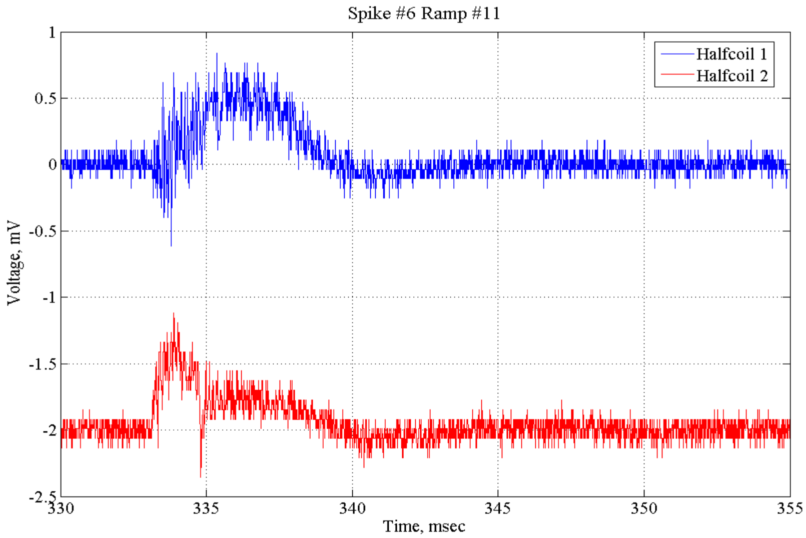

Spike #4 Ramp #11
Sum
Diff
Voltage, mV
Time, msec

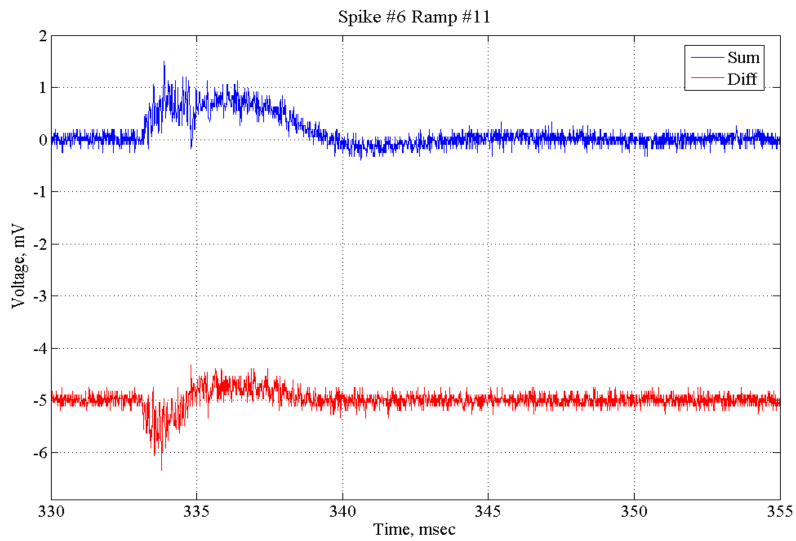

Moving Average Spike #4 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

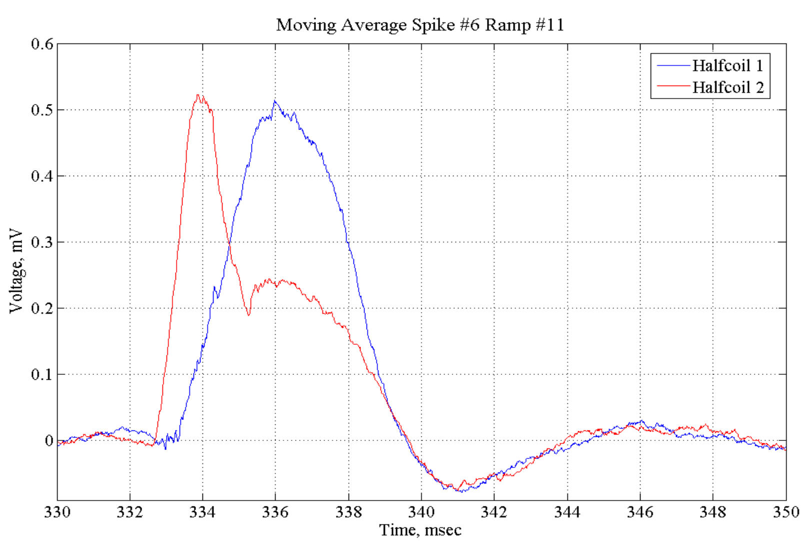

Spike #5 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

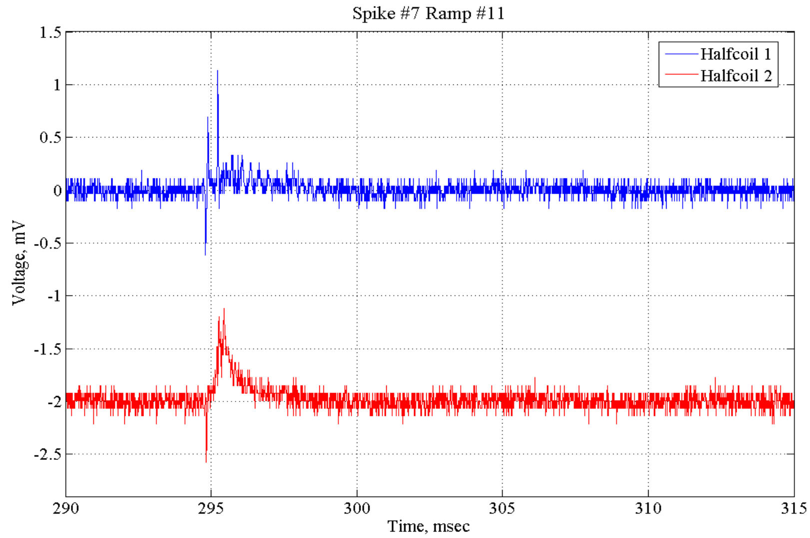

Spike #5 Ramp #11
Sum
Diff
Voltage, mV
Time, msec


Moving Average Spike #5 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

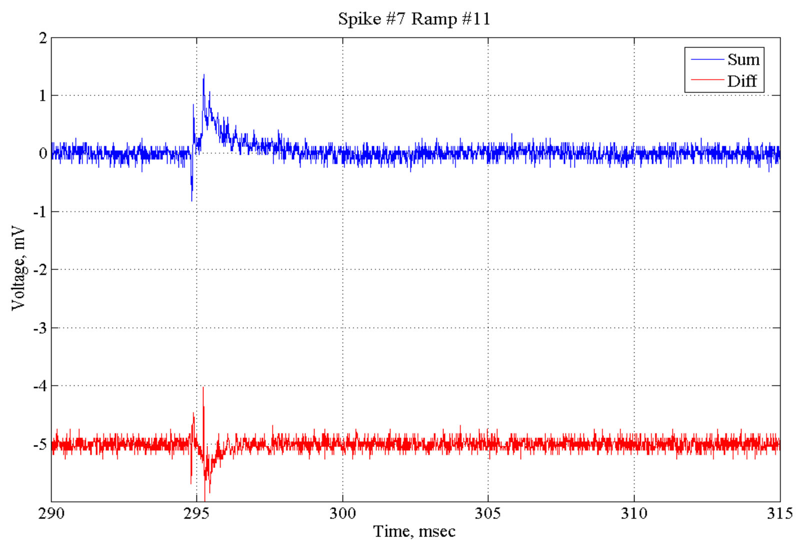

Spike #6 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
330
335
340
345
350
355


Spike #6 Ramp #11
Sum
Diff
Voltage, mV
Time, msec
2
1
0
-1
-2
-3
-4
-5
-6
330
335
340
345
350
355

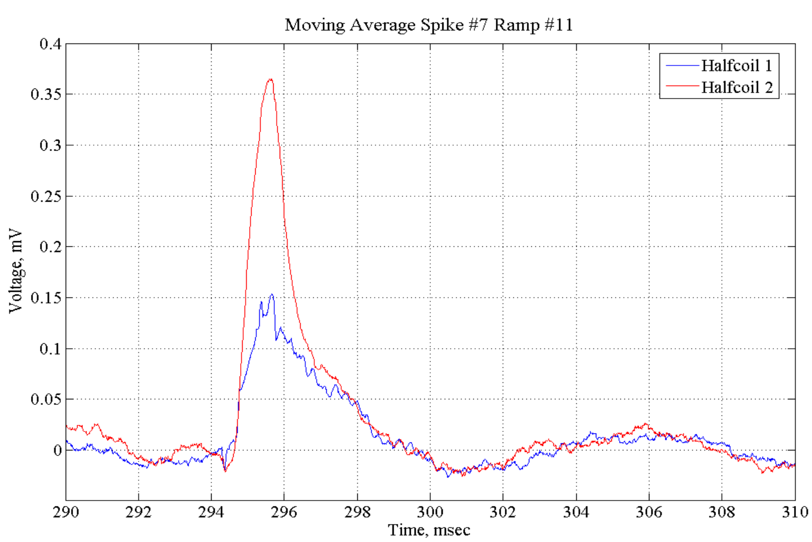

Moving Average Spike #6 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.6
0.5
0.4
0.3
0.2
0.1
0
330
332
334
336
338
340
342
344
346
348
350



Spike #7 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
290
295
300
305
310
315

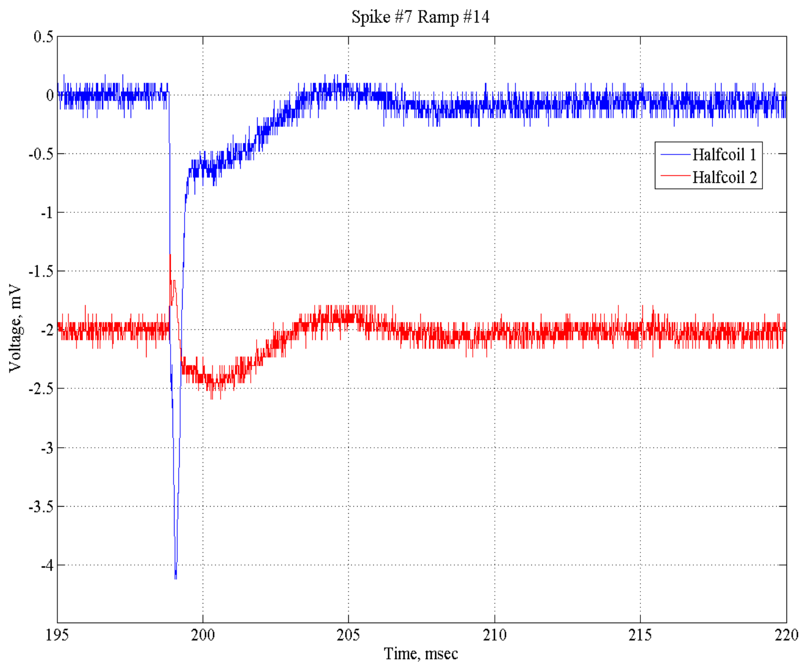


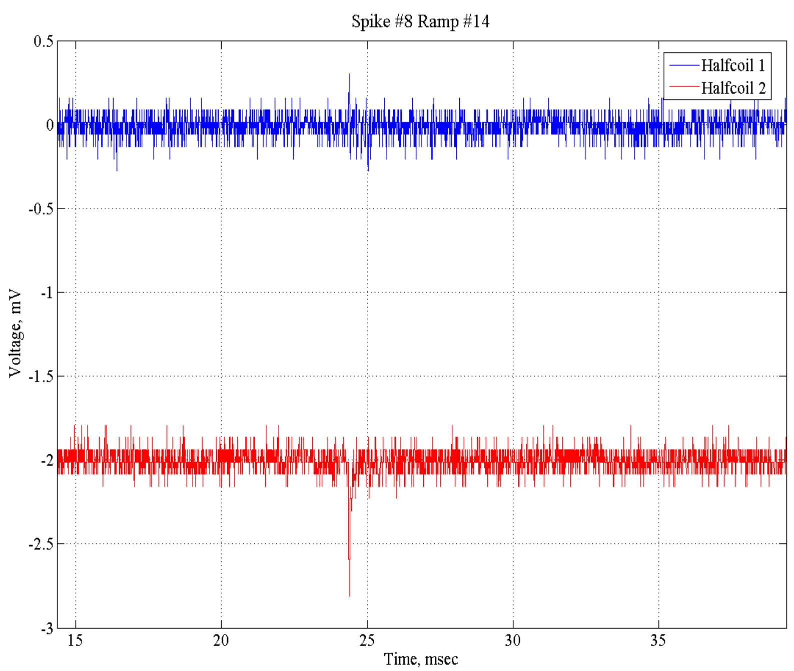
Spike #7 Ramp #11
Sum
Diff
Voltage, mV
Time, msec
2
1
0
-1
-2
-3
-4
-5
290
295
300
305
310
315

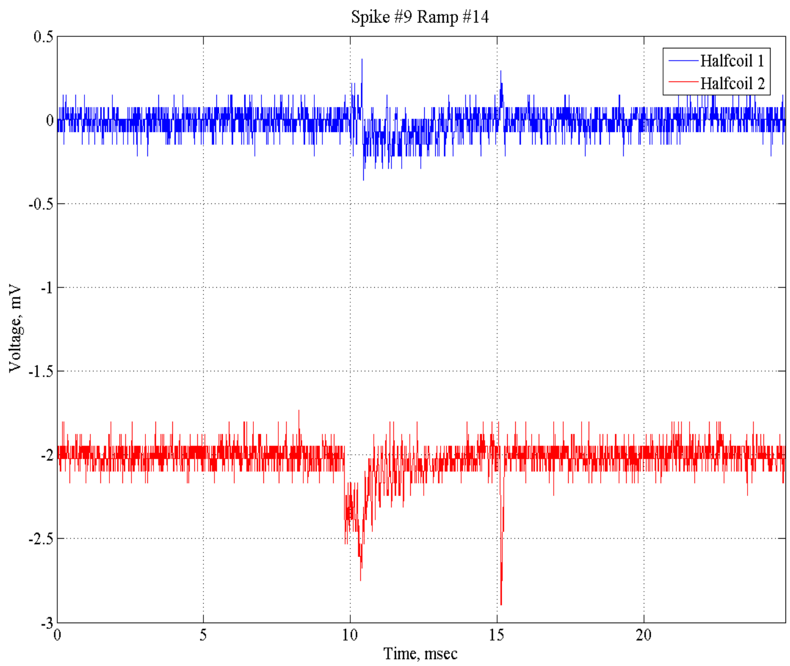


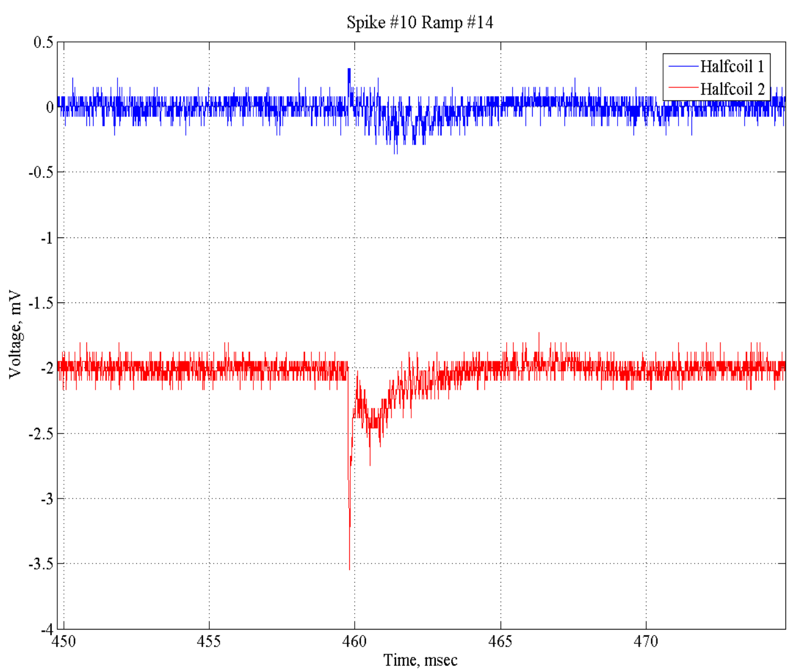
Moving Average Spike #7 Ramp #11
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
290
292
294
296
298
300
302
304
306
308
310

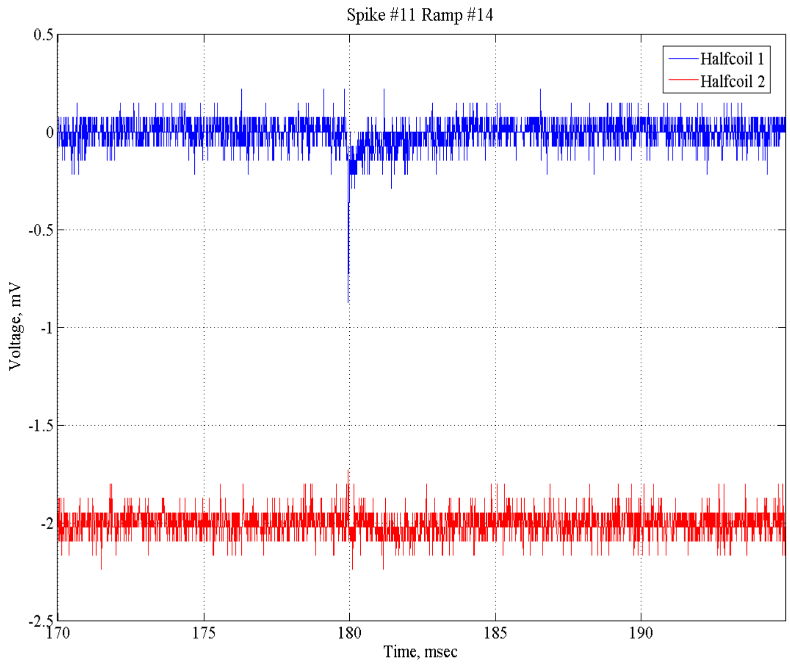
APPENDIX B – LOCAL MAGNETIZATION SPIKES



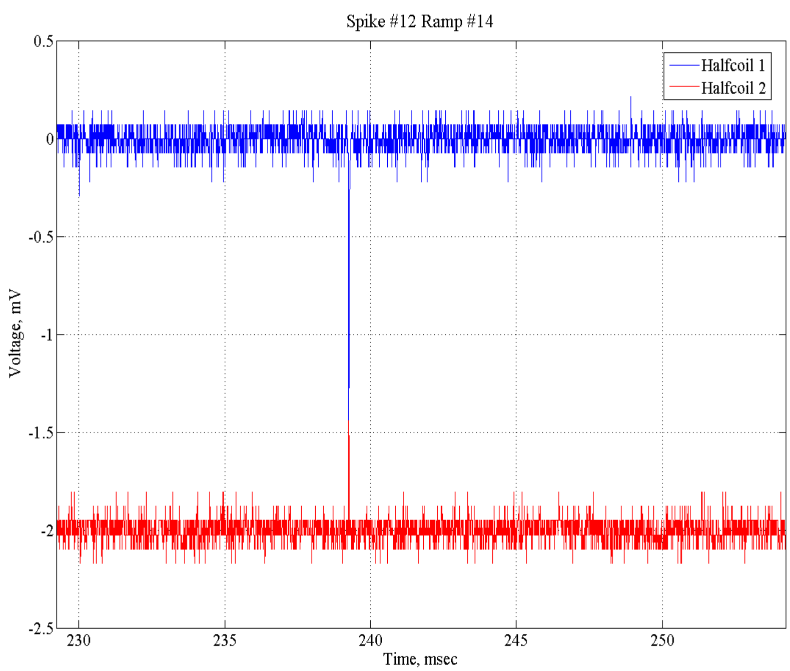



Spike #9 Ramp #14
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

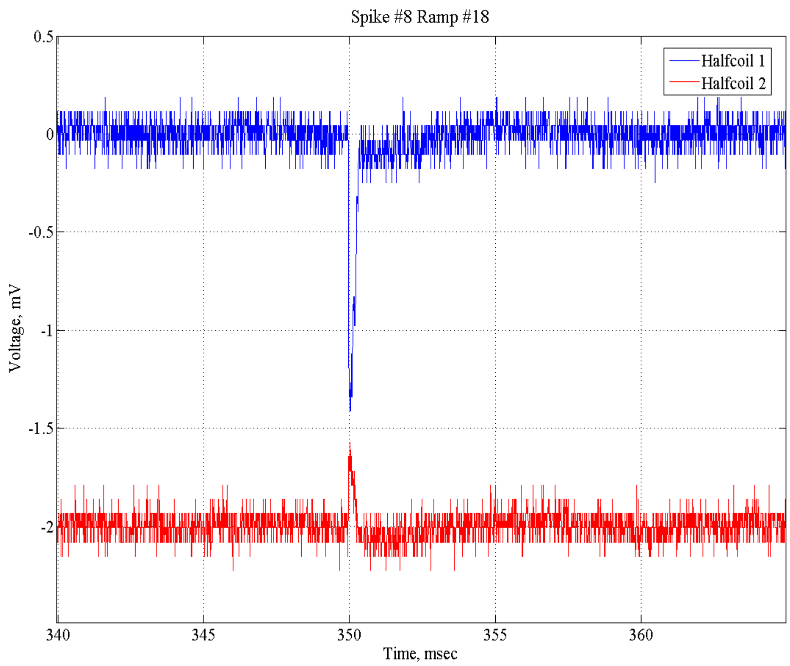

Spike #10 Ramp #14
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec



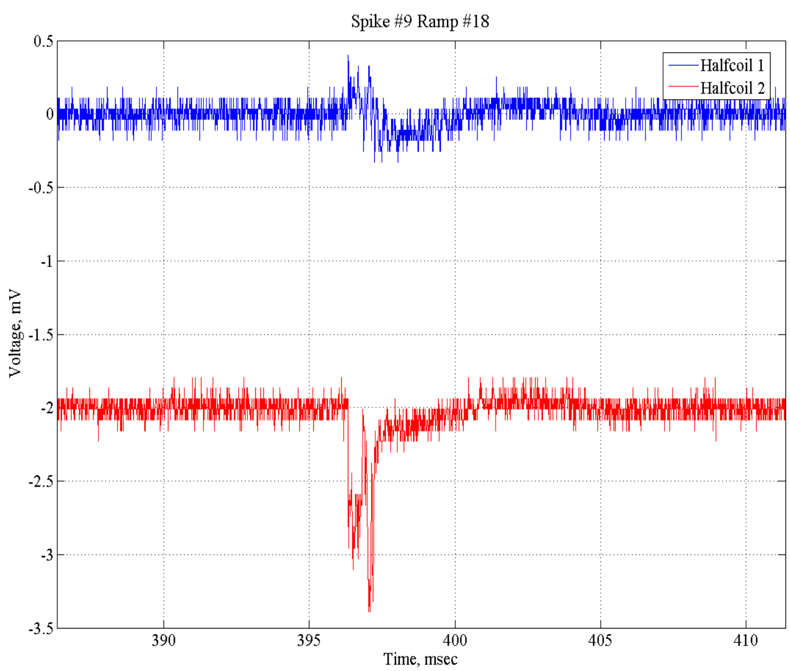
Spike #11 Ramp #14
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.5
0
-0.5
-1
-1.5
-2
-2.5
170
175
180
185
190



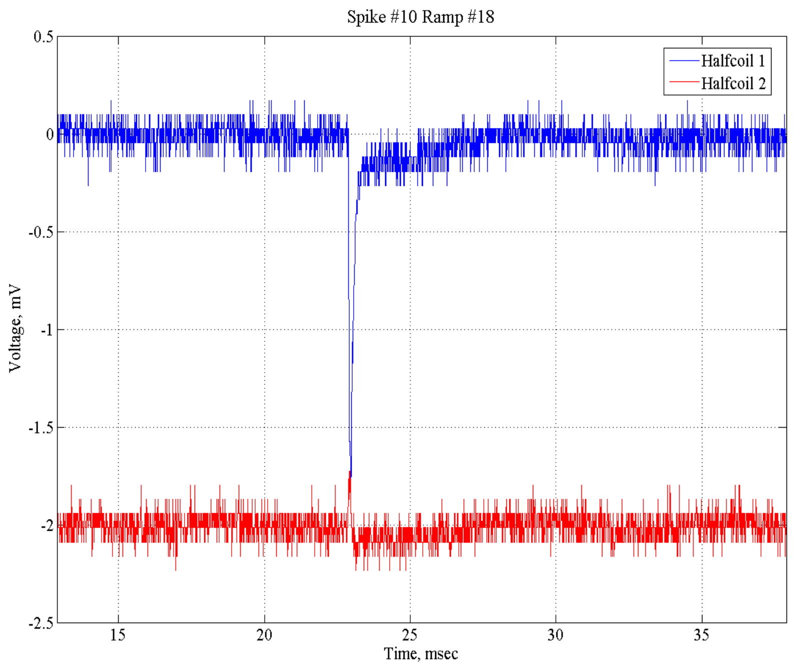
Spike #12 Ramp #14
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.5
0
-0.5
-1
-1.5
-2
-2.5
230
235
240
245
250

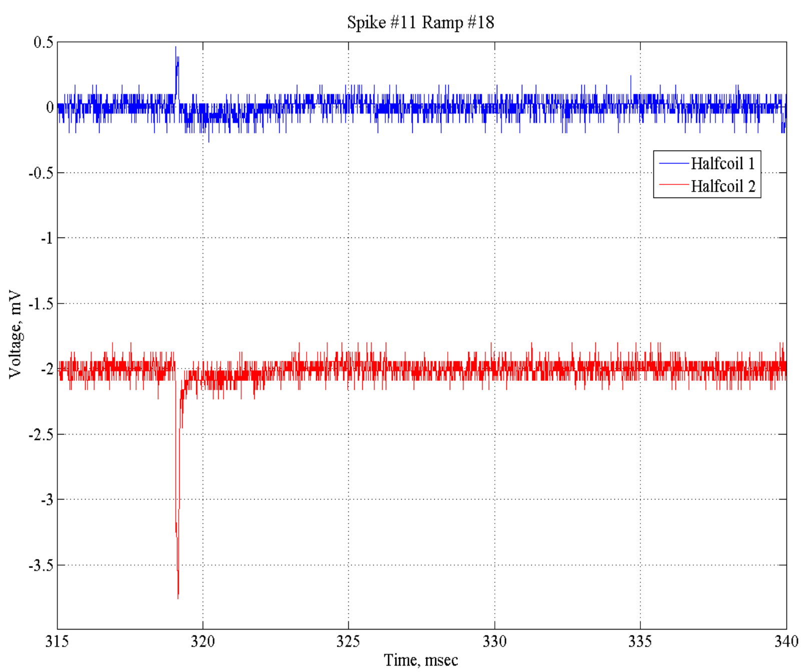


Spike #8 Ramp #18
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.5
0
-0.5
-1
-1.5
-2
340
345
350
355
360

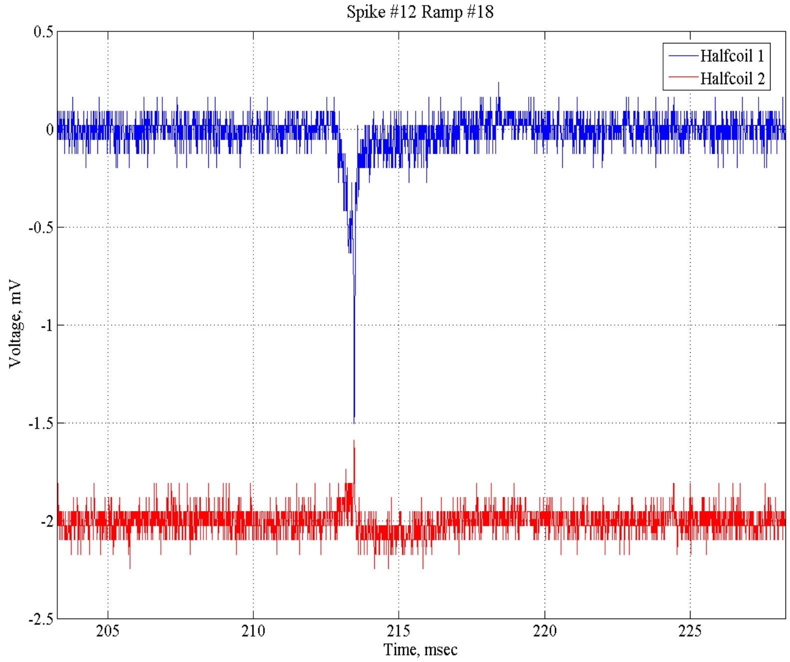


Spike #9 Ramp #18
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
390
395
400
405
410

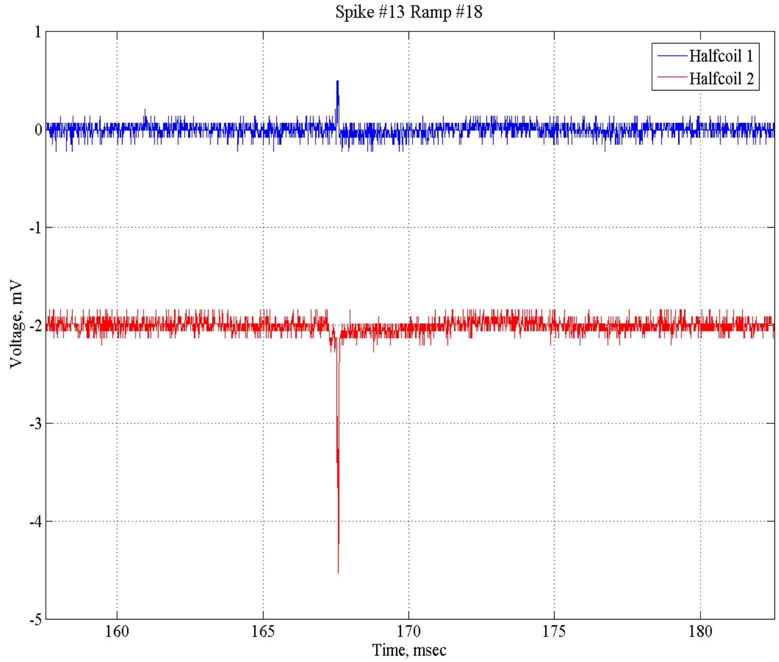

Spike #10 Ramp #18
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.5
0
-0.5
-1
-1.5
-2
-2.5
15
20
25
30
35

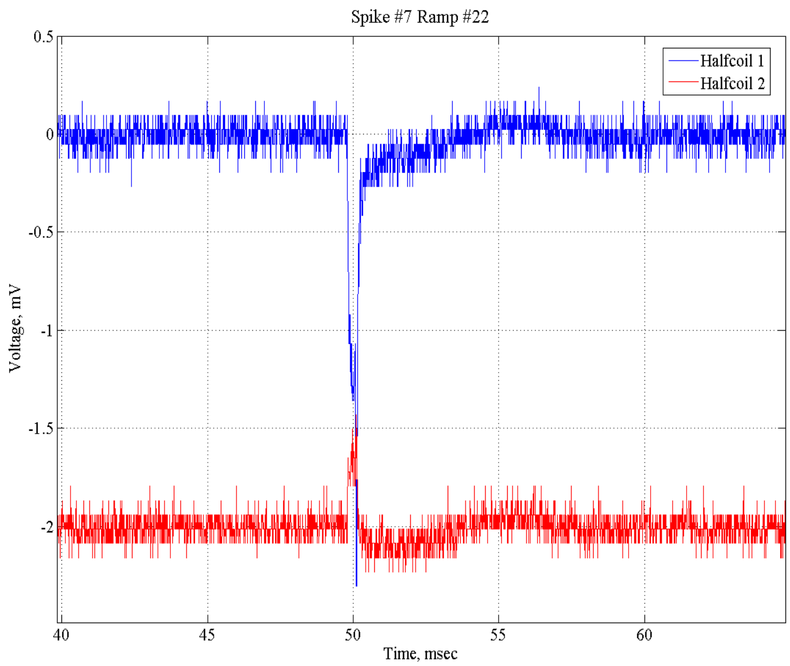

Spike #11 Ramp #18
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
315
320
325
330
335
340

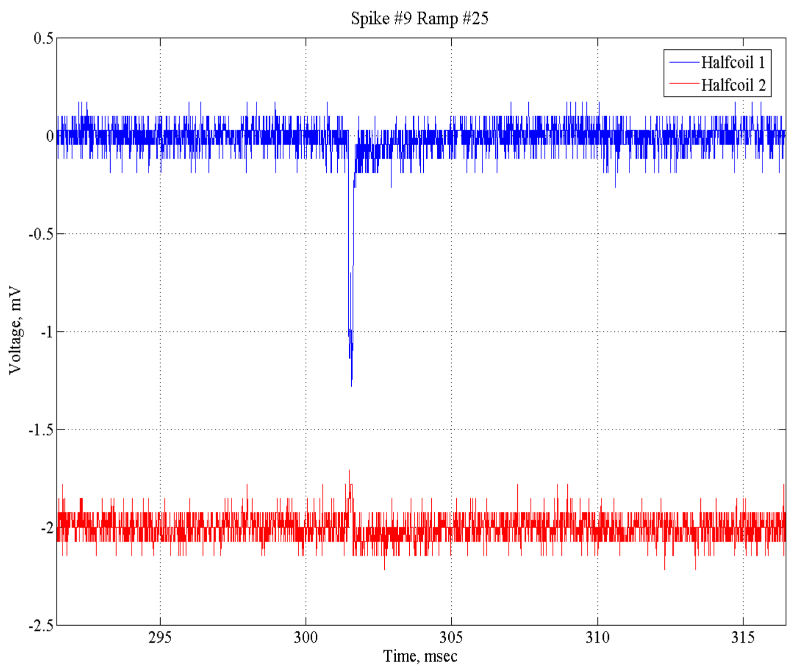
Spike #12 Ramp #18

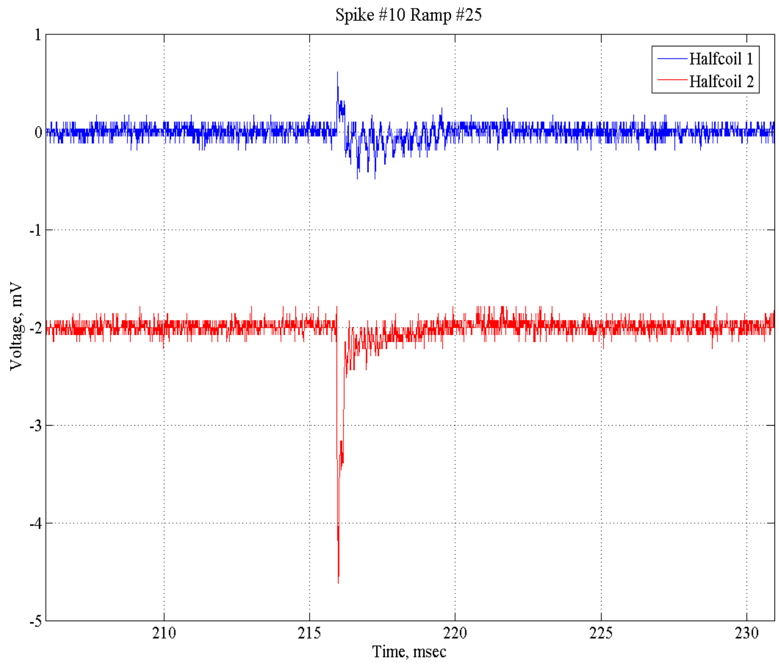


Spike #13 Ramp #18

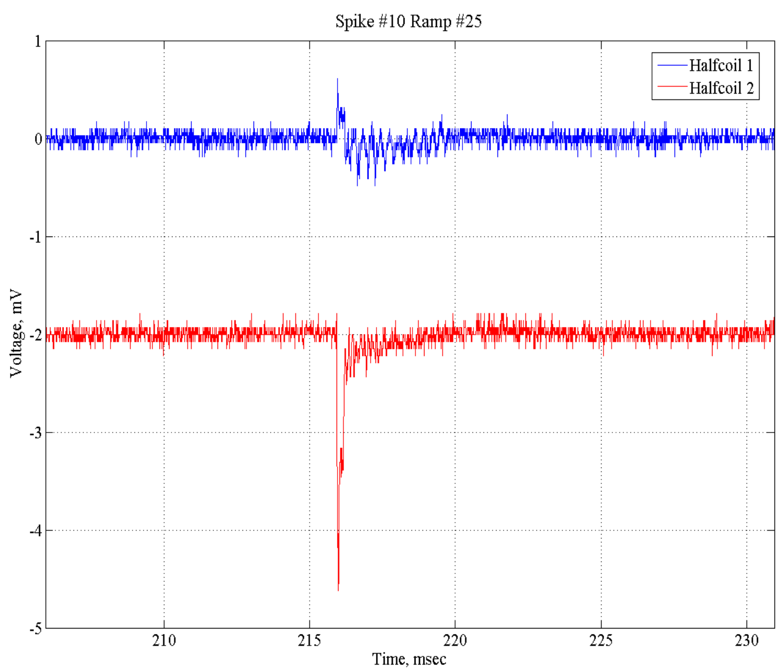



Spike #7 Ramp #22
Halfcoil 1
Halfcoil 2
0.5
0
-0.5
-1
-1.5
-2
40
45
50
55
60
Voltage, mV
Time, msec


Spike #9 Ramp #25
Halfcoil 1
Halfcoil 2
0.5
0
-0.5
-1
-1.5
-2
-2.5
295
300
305
310
315
Voltage, mV
Time, msec

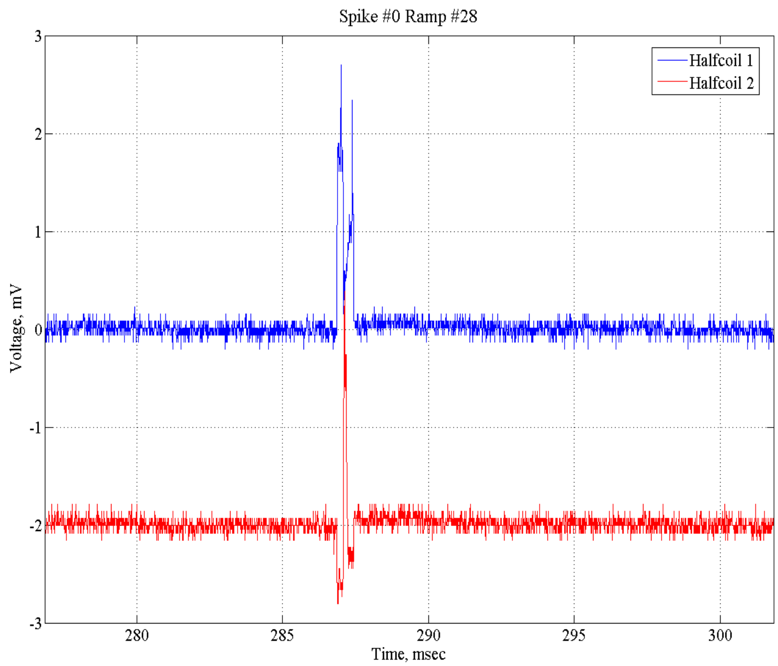


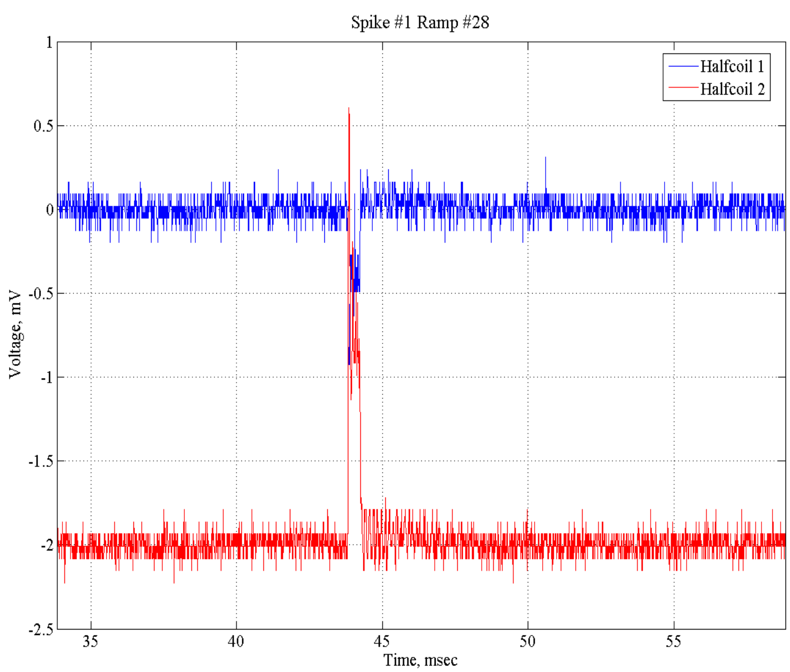
Spike #10 Ramp #25
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

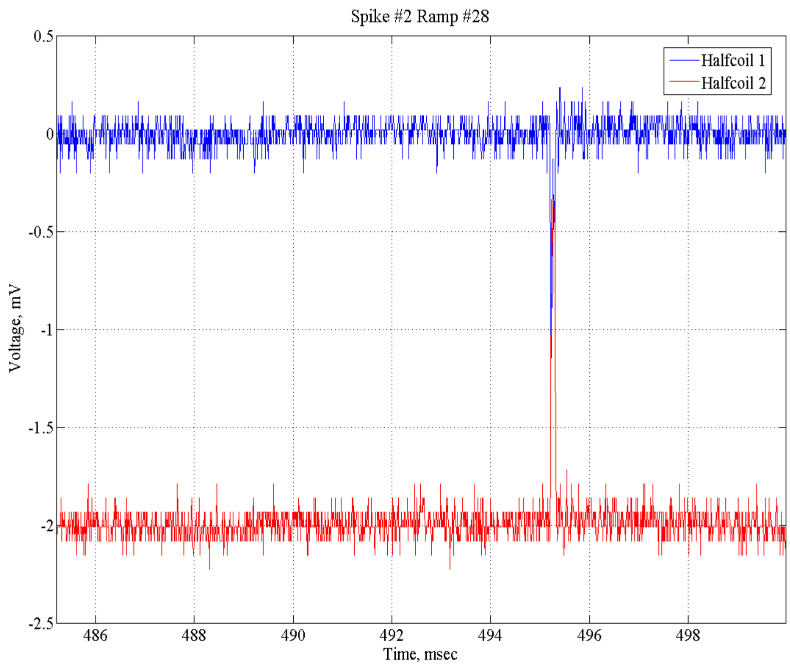


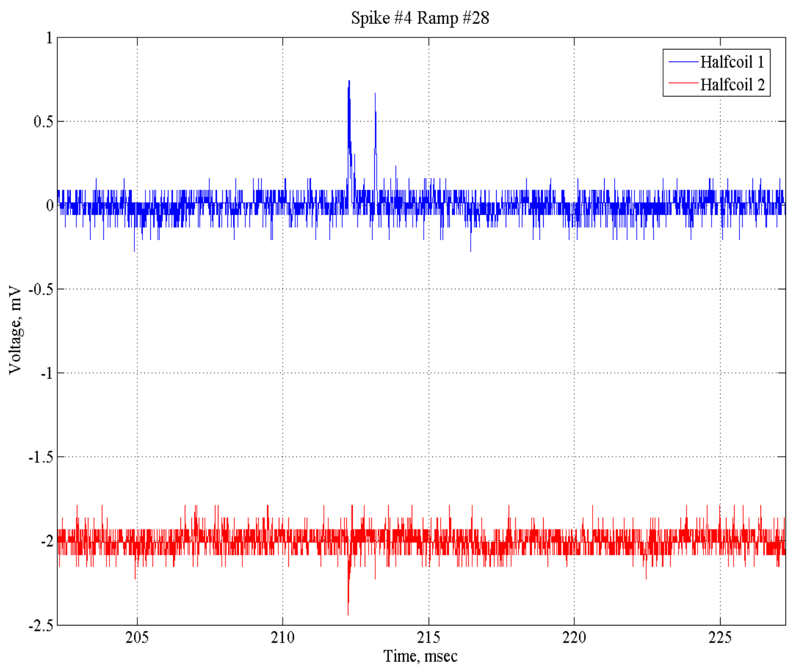
Spike #10 Ramp #25
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

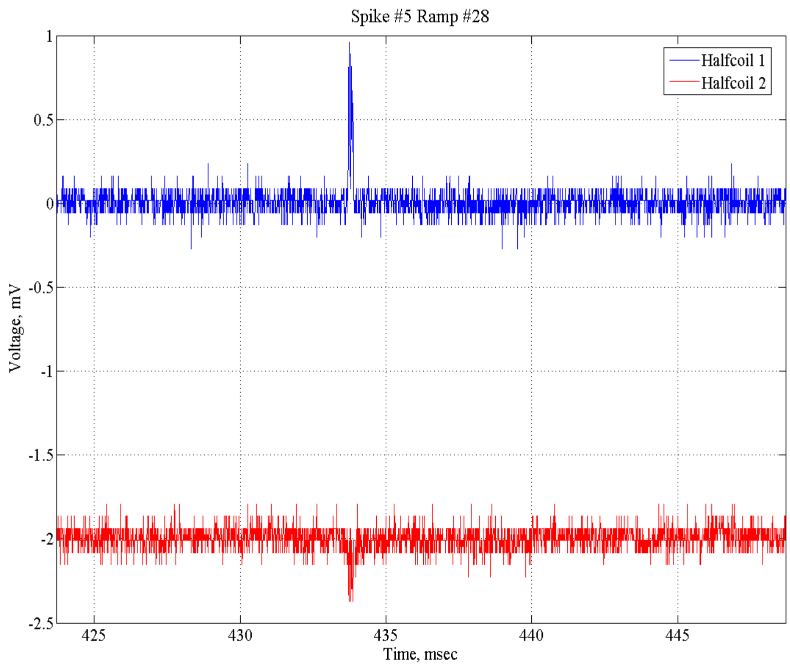
APPENDIX C TRANSPORT CURRENT SPIKES

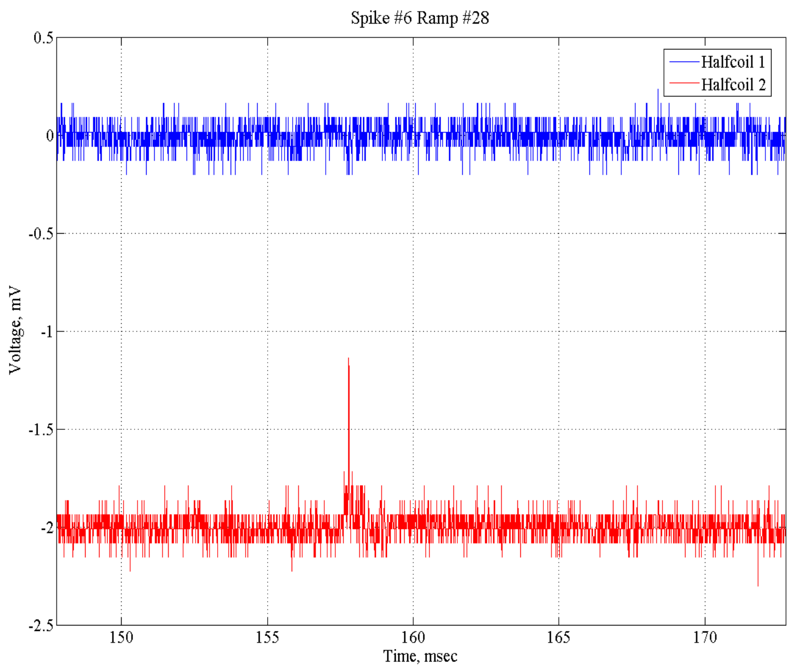


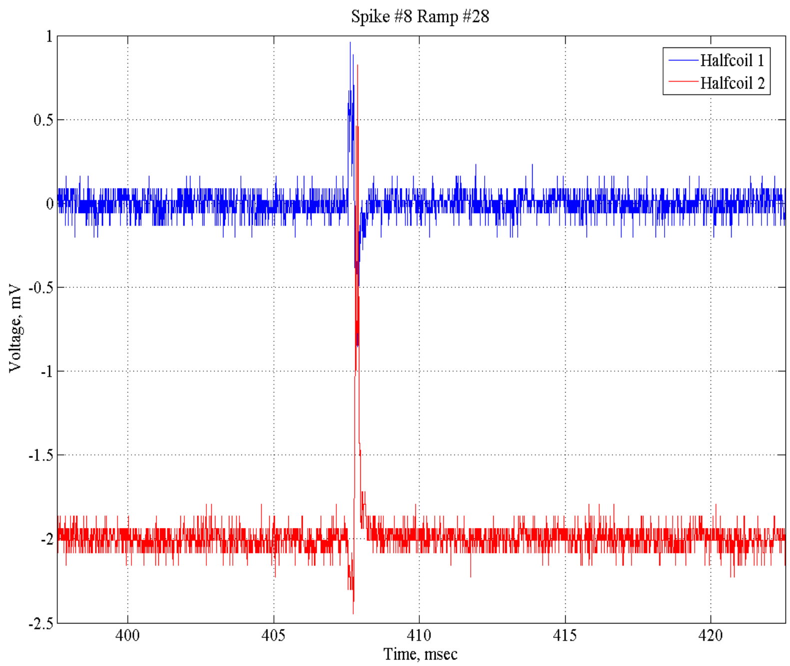


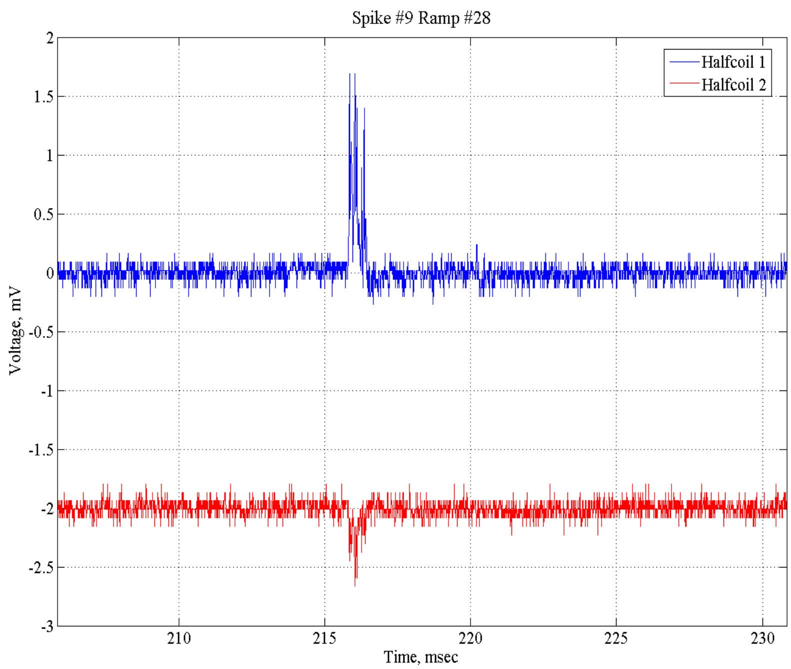

Spike #2 Ramp #28
Halfcoil 1
Halfcoil 2
Voltage, mV
0.5
0
-0.5
-1
-1.5
-2
-2.5
486
488
490
492
494
496
498
Time, msec

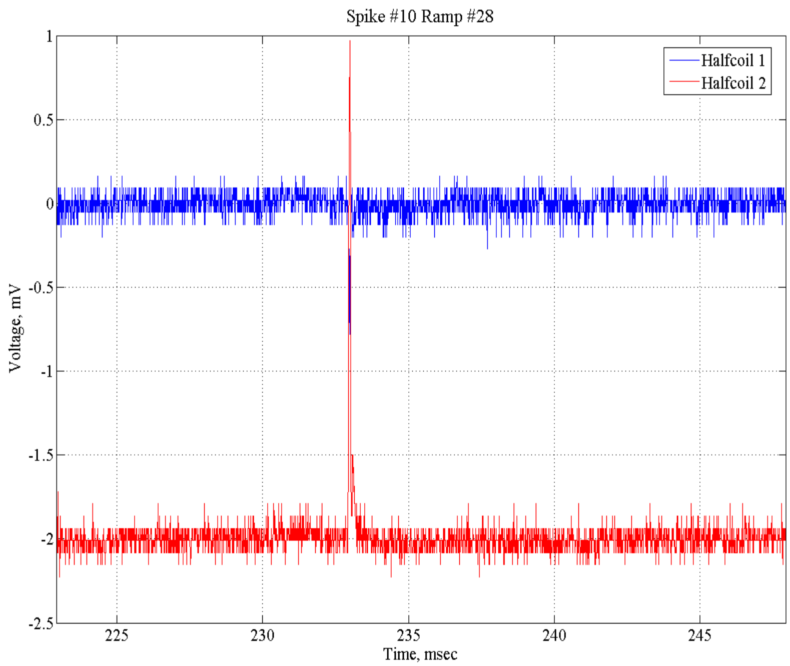

Spike #4 Ramp #28
Halfcoil 1
Halfcoil 2
Voltage, mV
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
205
210
215
220
225
Time, msec

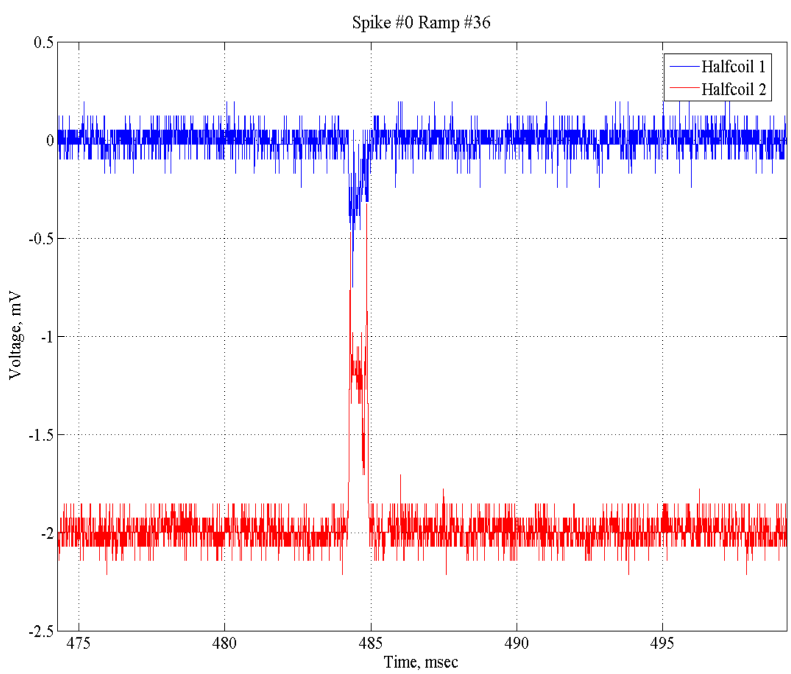

Spike #5 Ramp #28
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
425
430
435
440
445

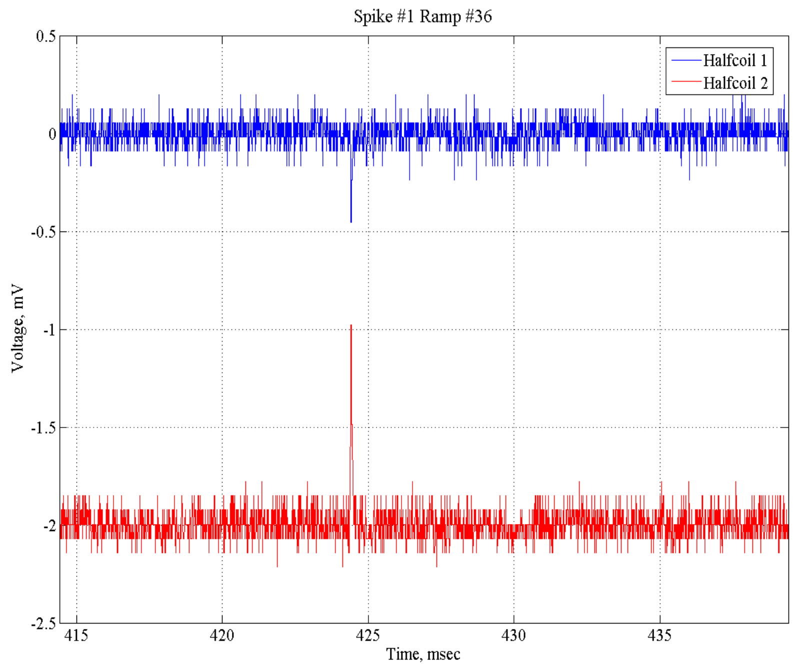

Spike #6 Ramp #28
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.5
0
-0.5
-1
-1.5
-2
-2.5
150
155
160
165
170

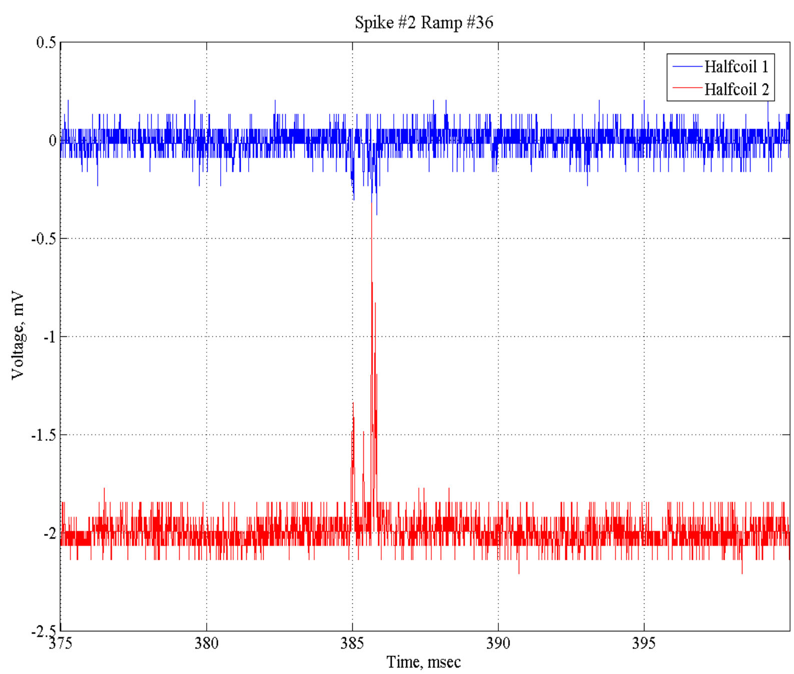

Spike #8 Ramp #28
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
400
405
410
415
420


Spike #9 Ramp #28
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
210
215
220
225
230

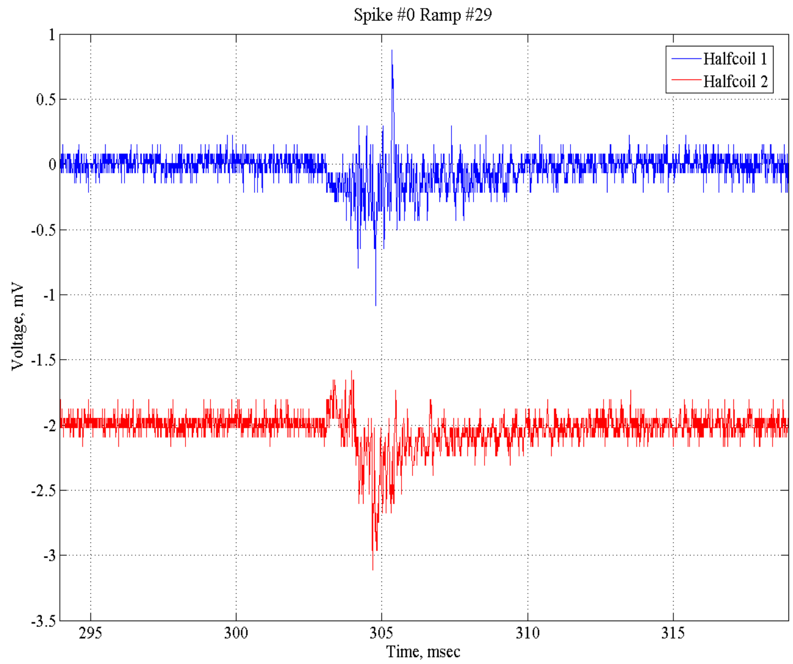

Spike #10 Ramp #28
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

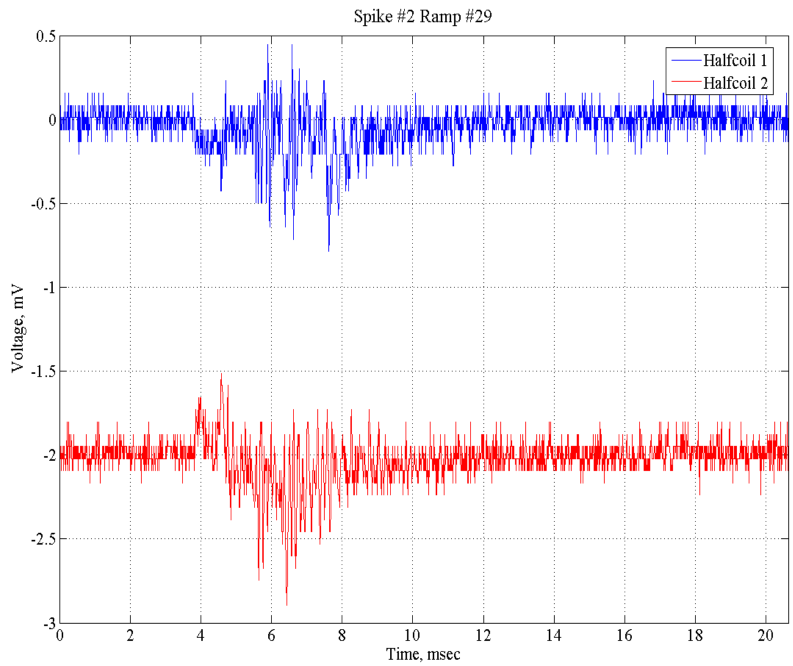

Spike #0 Ramp #36
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec

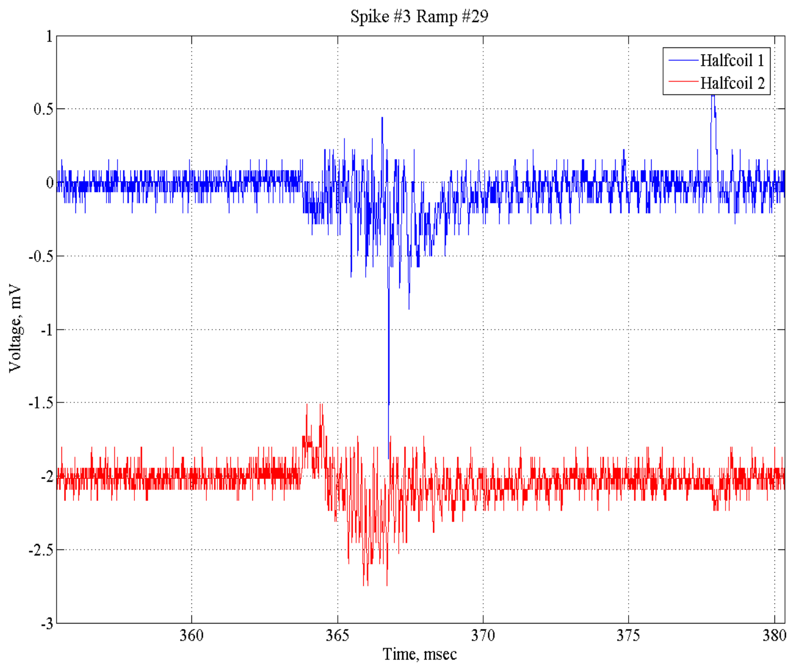

Spike #1 Ramp #36
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.5
0
-0.5
-1
-1.5
-2
-2.5
415
420
425
430
435


Spike #2 Ramp #36
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.5
0
-0.5
-1
-1.5
-2
-2.5
375
380
385
390
395

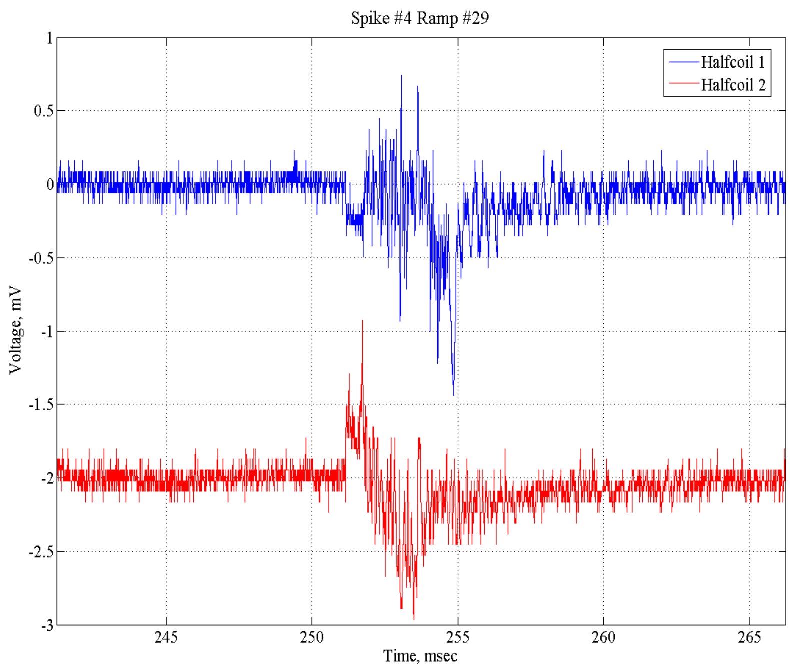
APPENDIX D MIXED SPIKES



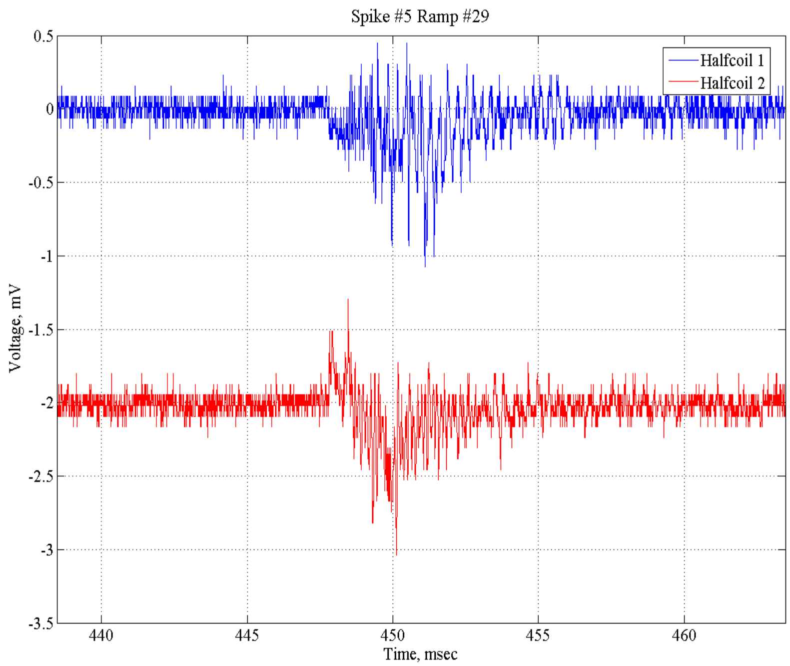


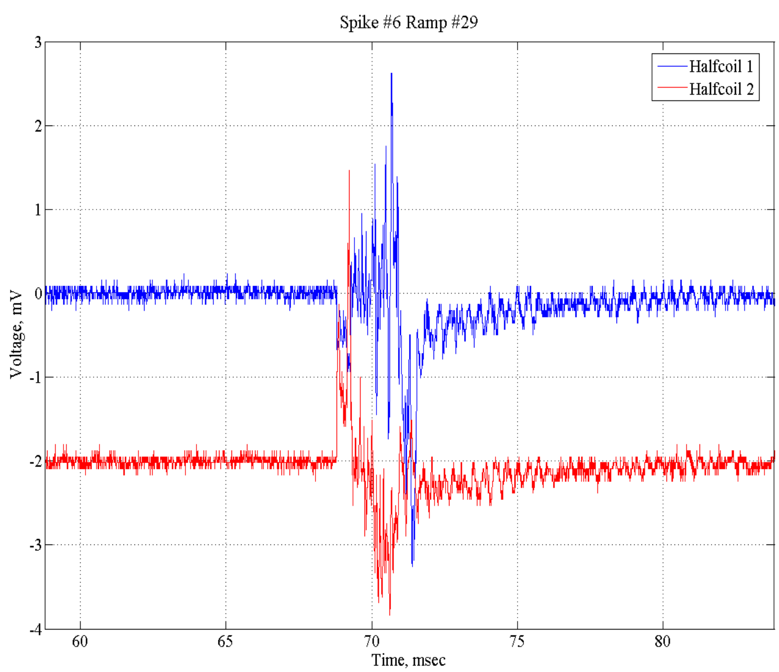


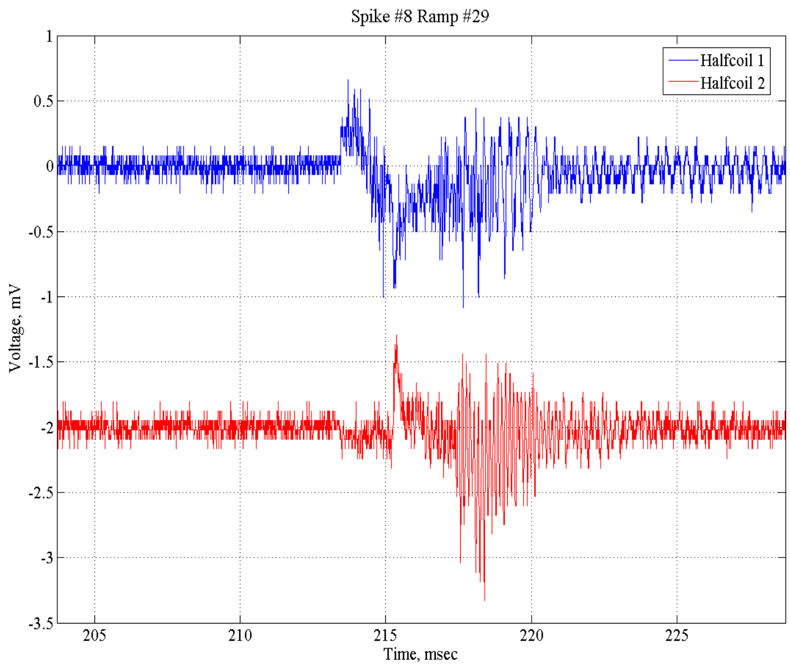
Spike #3 Ramp #29
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
360
365
370
375
380

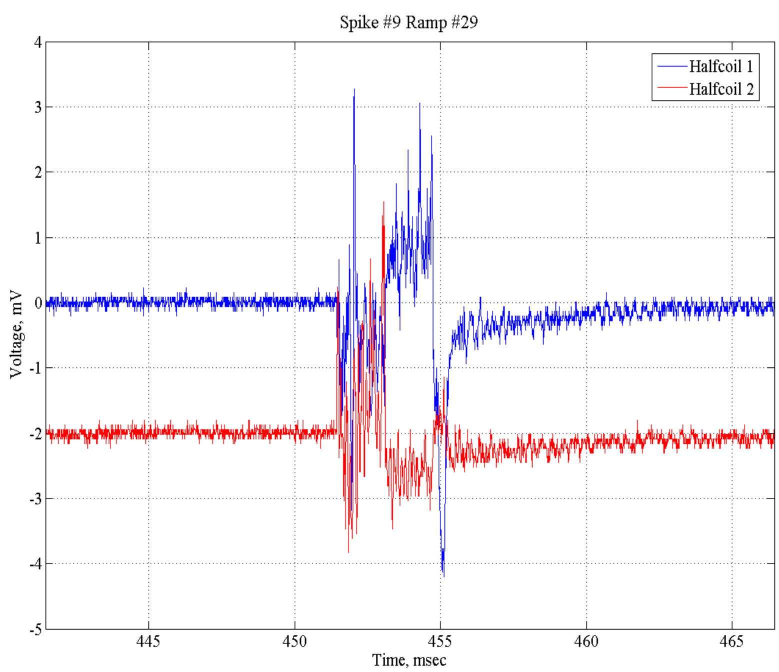


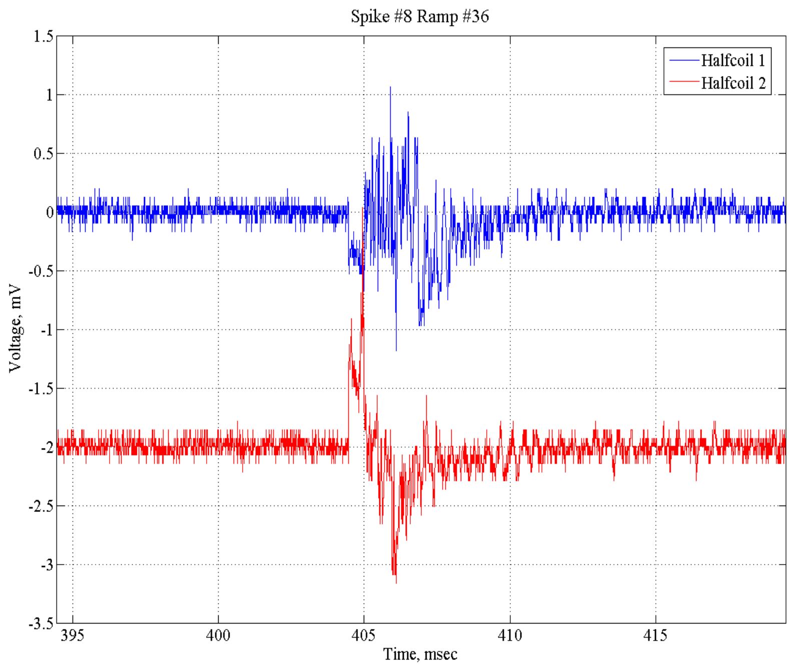
Spike #4 Ramp #29
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
245
250
255
260
265

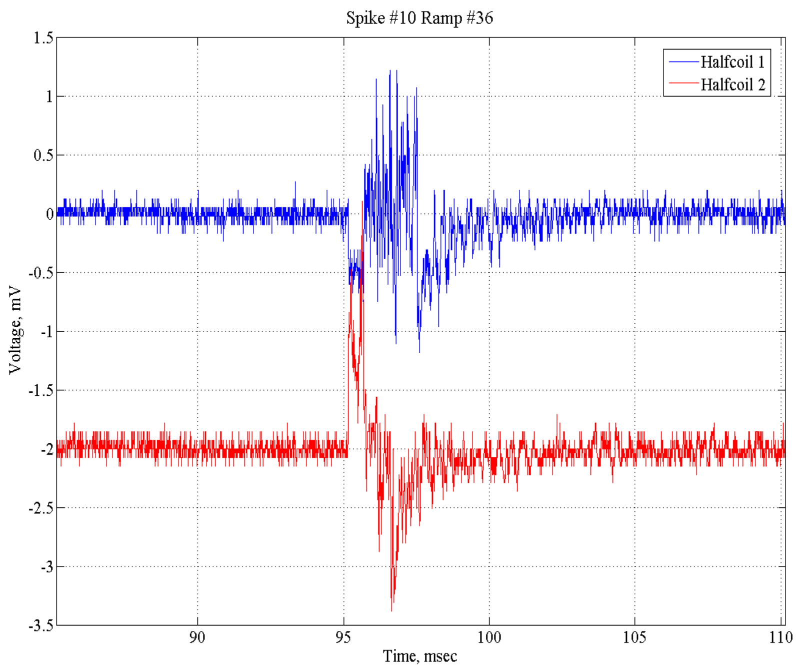

Spike #5 Ramp #29
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
440
445
450
455
460

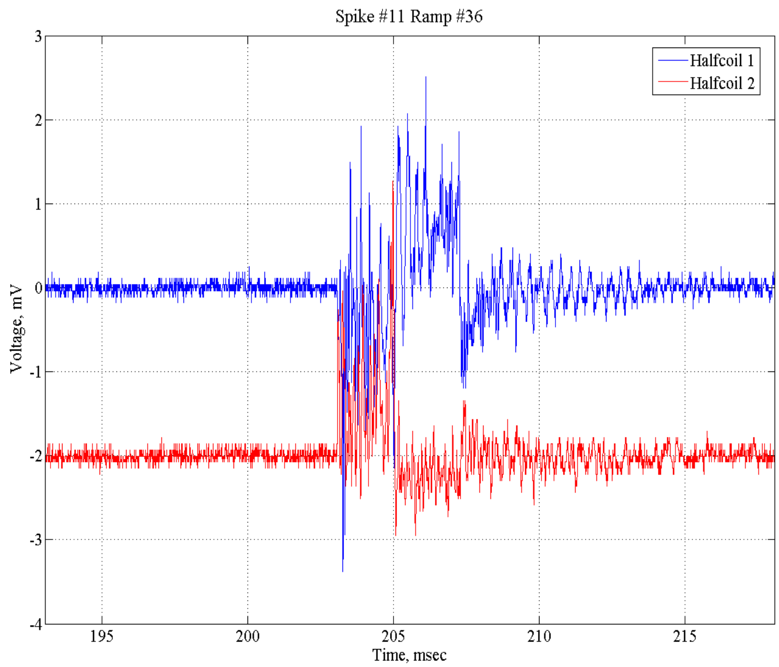

Spike #6 Ramp #29
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
3
2
1
0
-1
-2
-3
-4
60
65
70
75
80


Spike #8 Ramp #29
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
205
210
215
220
225


Spike #9 Ramp #29
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
4
3
2
1
0
-1
-2
-3
-4
-5
445
450
455
460
465


Spike #8 Ramp #36
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
395
400
405
410
415


Spike #10 Ramp #36
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
90
95
100
105
110



Spike #11 Ramp #36
Halfcoil 1
Halfcoil 2
Voltage, mV
Time, msec
3
2
1
0
-1
-2
-3
-4
195
200
205
210
215